Radiation Hardened Infrared Focal Plane Arrays

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Introduction: Goal, Specifications and Challenges

EPIR

Goal:

Fabrication of cost-efficient video cameras using infrared sensors that have high resistance to radiation.

Specifications

- Target temperature: ~300°C
- Sensitive in the 5 μm and longer spectral range (MWIR)
- Operate at standard frame rates (>25 frames/s, hence the maximum sum of the integration time and the data transfer time up to 40ms)

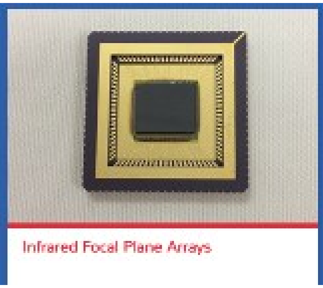
Challenges:

Radiation tolerance for prolonged operation

- Under neutron fluxes (10^5 n cm^{-2} s^{-1}) => short period of time
- Total absorbed dose of ~ 1MRad/yr. => Total dose (TD) effects

Company Overview

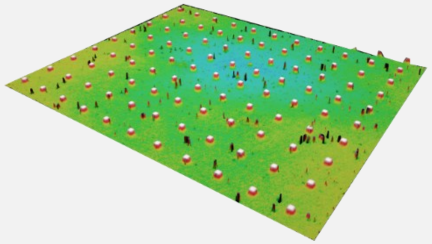
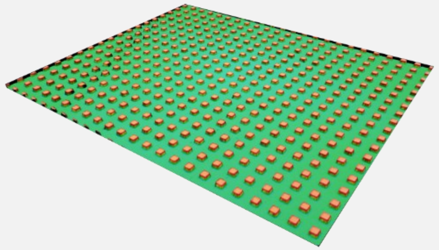
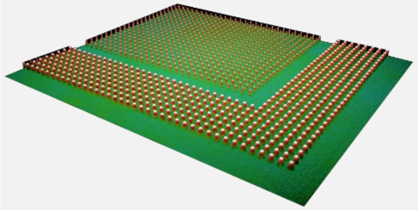
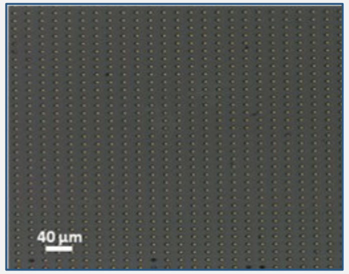
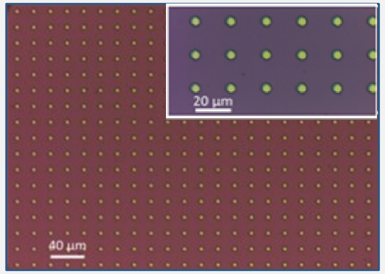
EPIR : R&D and Commercialization for II-VI based Material, Device and System Technologies



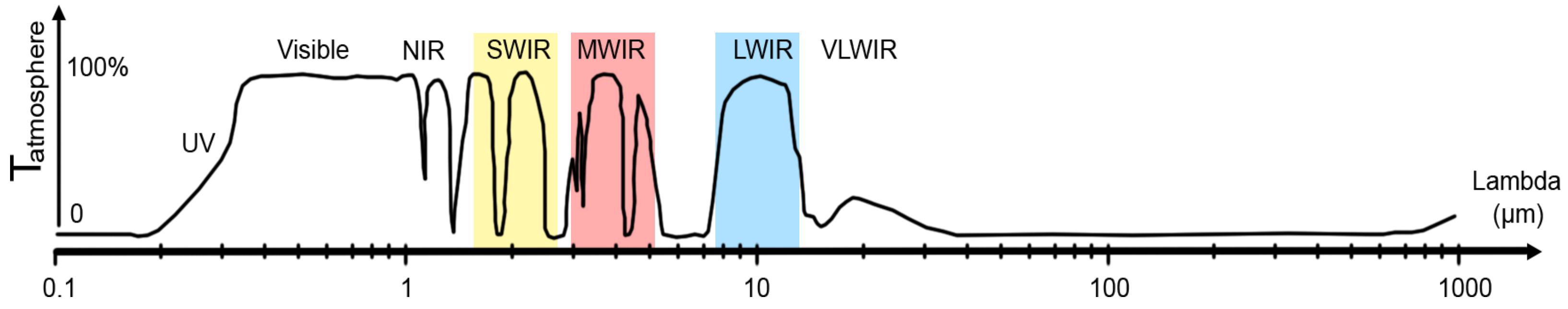

- ❖ **Pioneered molecular beam epitaxy (MBE) HgCdTe material growth**
- ❖ **Decades of experience with II-VI material and device fabrication and testing**
- ❖ **Headquartered in Bolingbrook, IL**
  - ➢ Commercial supplier of MBE materials and devices to a broad customer base
  - ➢ Provider of materials, focal plane arrays and sensors solutions
  - ➢ Close collaboration with two DOE National Labs from Chicago area: ANL (7 miles, CNM) and Fermilab (15 miles)

1. **II-VI Material Manufacturing**
   - ➢ Grow II-VI materials to enable standard and custom imaging products
   - ➢ HgCdTe on CdZnTe and Si-based substrates (using CdTe buffer layer)
2. **Focal Plane Arrays and Camera Development and Production**
   - ➢ Standard and specialty array detectors, FPAs and imaging sensors
3. **R&D Solutions using II-VI Technology**
   - ➢ Material, device & system modeling, optimization, fabrication and testing
   - ➢ Full process development to meet customer specifications

Infrared Focal Plane Array Manufacturing

EPIR, Inc.	Commercial-grade Solutions			Custom Solutions	
Format	320×256 30 µm pitch	640×512 15 µm pitch	1280×720 8 µm pitch	640×512 20 µm pitch	1280×512 20 µm pitch
Relative Die Size	20×11mm	20×11mm	21×10mm	23×14mm	30×18mm
Layout					

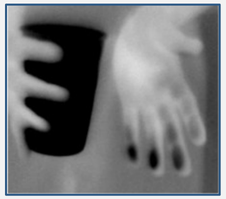
- EPIR manufactures both standard and custom devices in the NIR to LWIR range



NIR on Si, 298K

MWIR on CZT, 140K

LWIR on CZT, 85K



eSWIR on Si, 195K

MWIR on Si, 110K

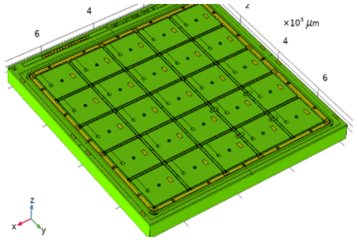
LWIR on CZT, 85K

Synergistic DOE Activities

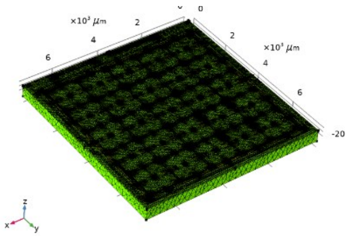
Advanced integration technology

- Integration of ETROC1/ETROC2 with LGAD

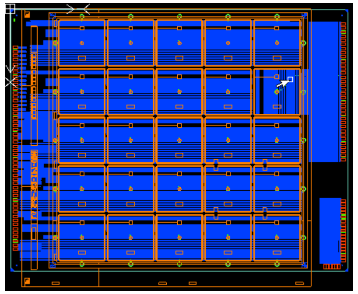
Thermal stress aware design

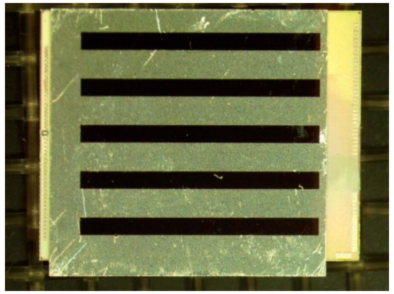


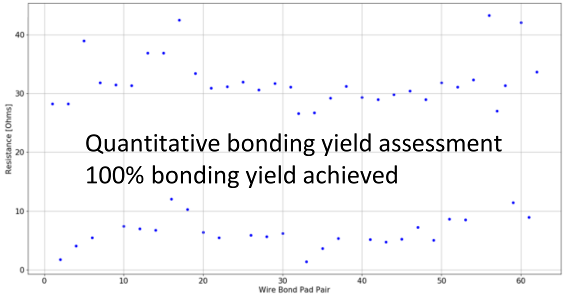
As designed



As integrated

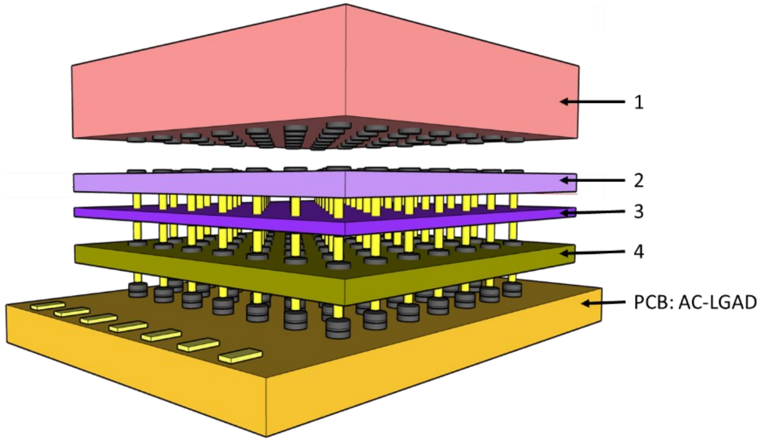






Multi-tier, small pixel ASIC

- VTROC: Vertical Timing Read Out Circuit

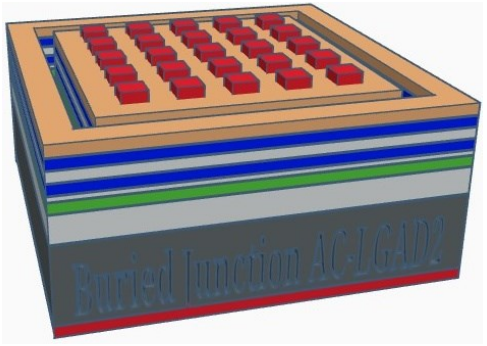


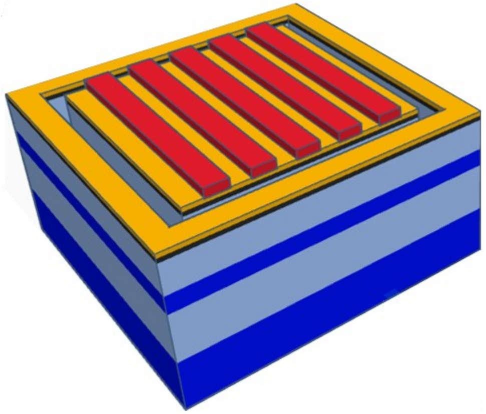
1. Detector: Small-pixel AC-LGAD
2. Front end preamp + discriminator + charge injector
3. Circular buffer memory array + readout logic
4. PCB: AC-LGAD

- 250µm pixel pitch
- 8×8 pixels
- Multi-tier ASICs
- 4-tier integration scheme

Radiation tolerant LGAD/AC-LGAD

- Advanced LGAD and AC-LGAD designs



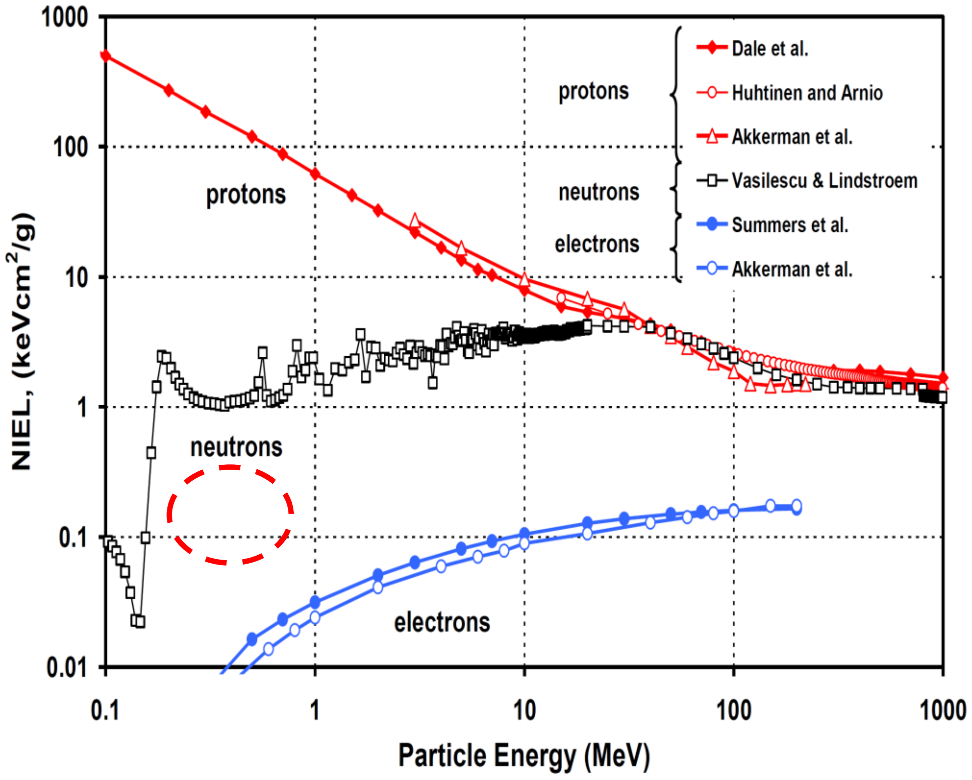


- Multi-layer epitaxial growth
- *In-situ* doping allows design flexibility

Displacement Damage Effects in HgCdTe and Related Materials

Neutrons cause FPA degradation mainly through displacement damage effects. Damage is characterized by Non-Ionizing Energy Loss (NIEL).

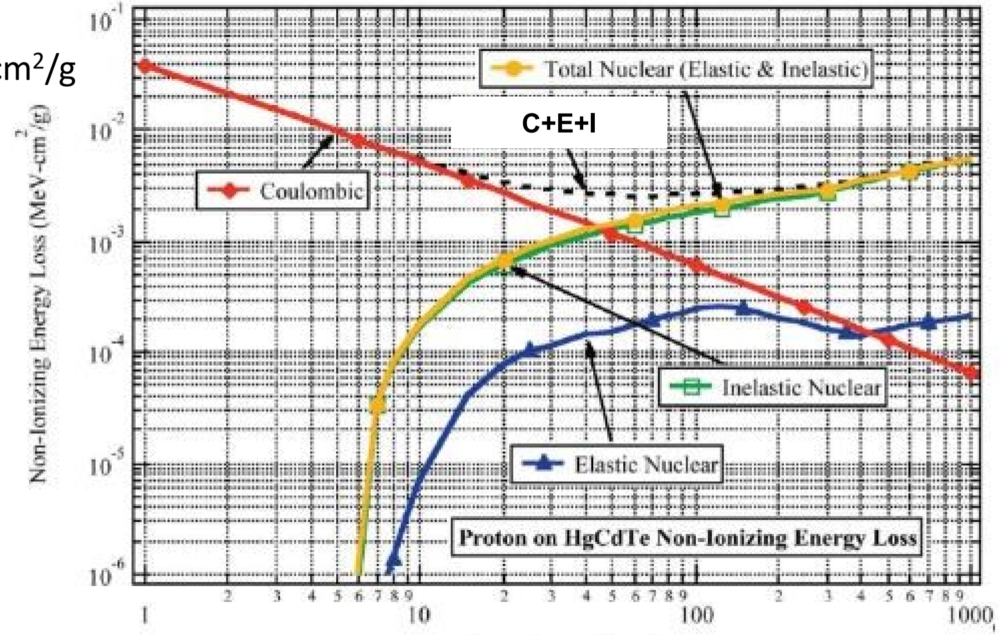
Non-Ionizing Energy Loss (NIEL) Si

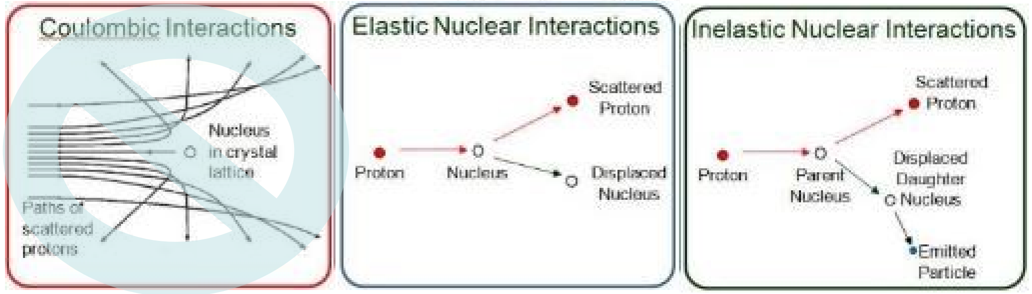


Final Test Guideline from Surrey Satellite Technology Limited, Guildford, Surrey
GU2 7YE, UK (2014)

Non-Ionizing Energy Loss (NIEL) HgCdTe (proton)

×1000
for keVcm²/g





J.E. Hubbs, et al., IEEE Trans. Nucl. Sci. **54**, 2435 (2007)
V. M. Cowan, C. P. Morath, J. E. Hubbs, Appl. Phys. Lett. **101**, 251108 (2012)

Project/R&D Objectives

EPIR

1. HgCdTe material growth and characterization

2. Design devices and photomasks with sub-pixel pattern optimization

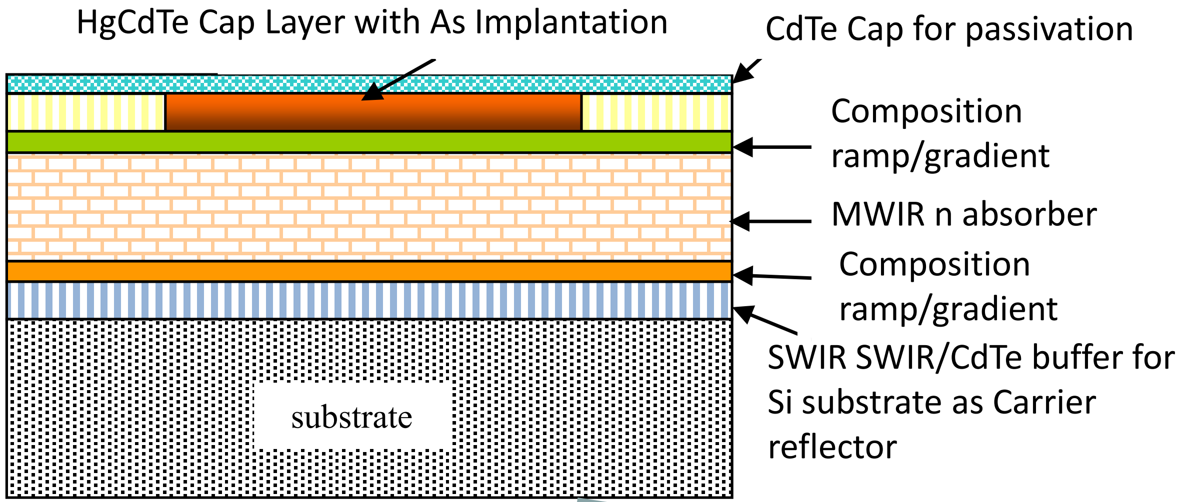
3. Fabrication of detectors with improved radiation hardness

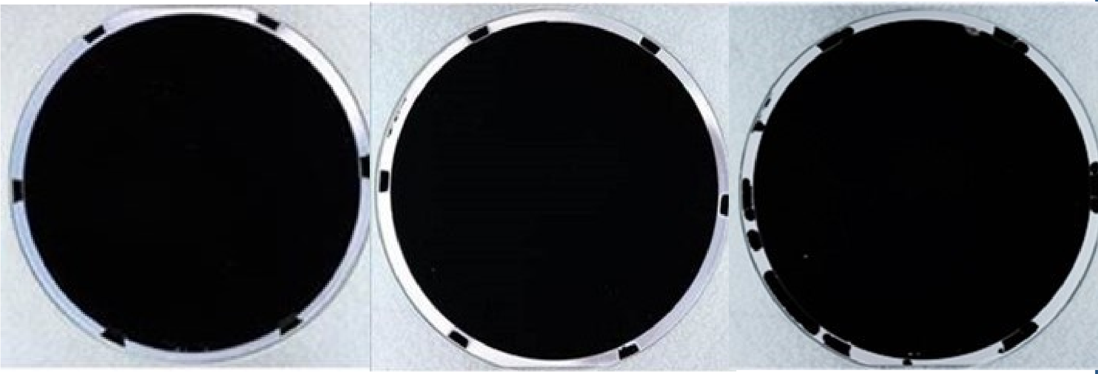
4. Integration of the detectors with radiation-hardened ROIC

5. Packaging and testing detectors and cameras under neutron flux

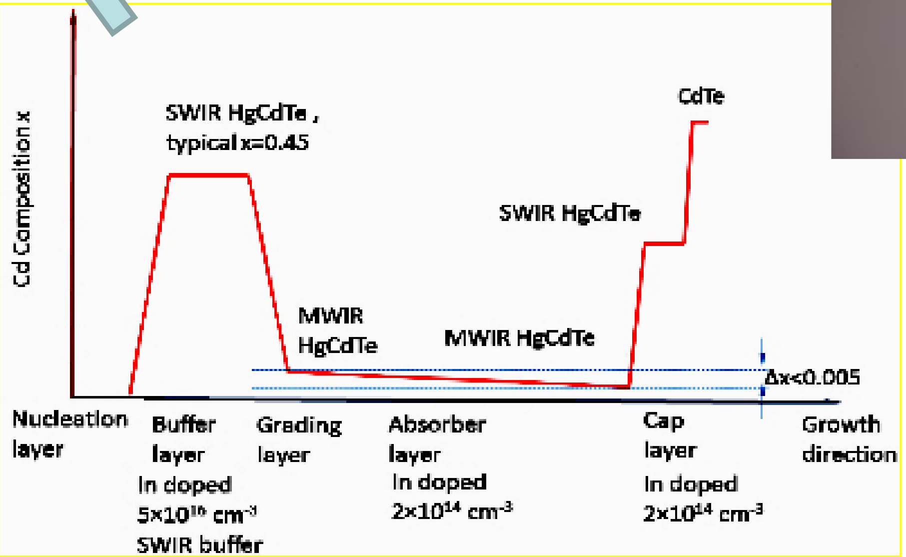
Growth and Characterization of HgCdTe Heterostructures

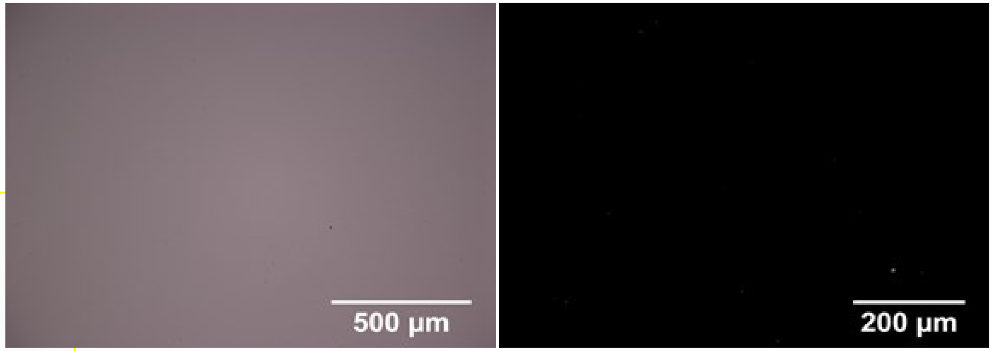
1. Design double layer planar heterostructures (DLPH)





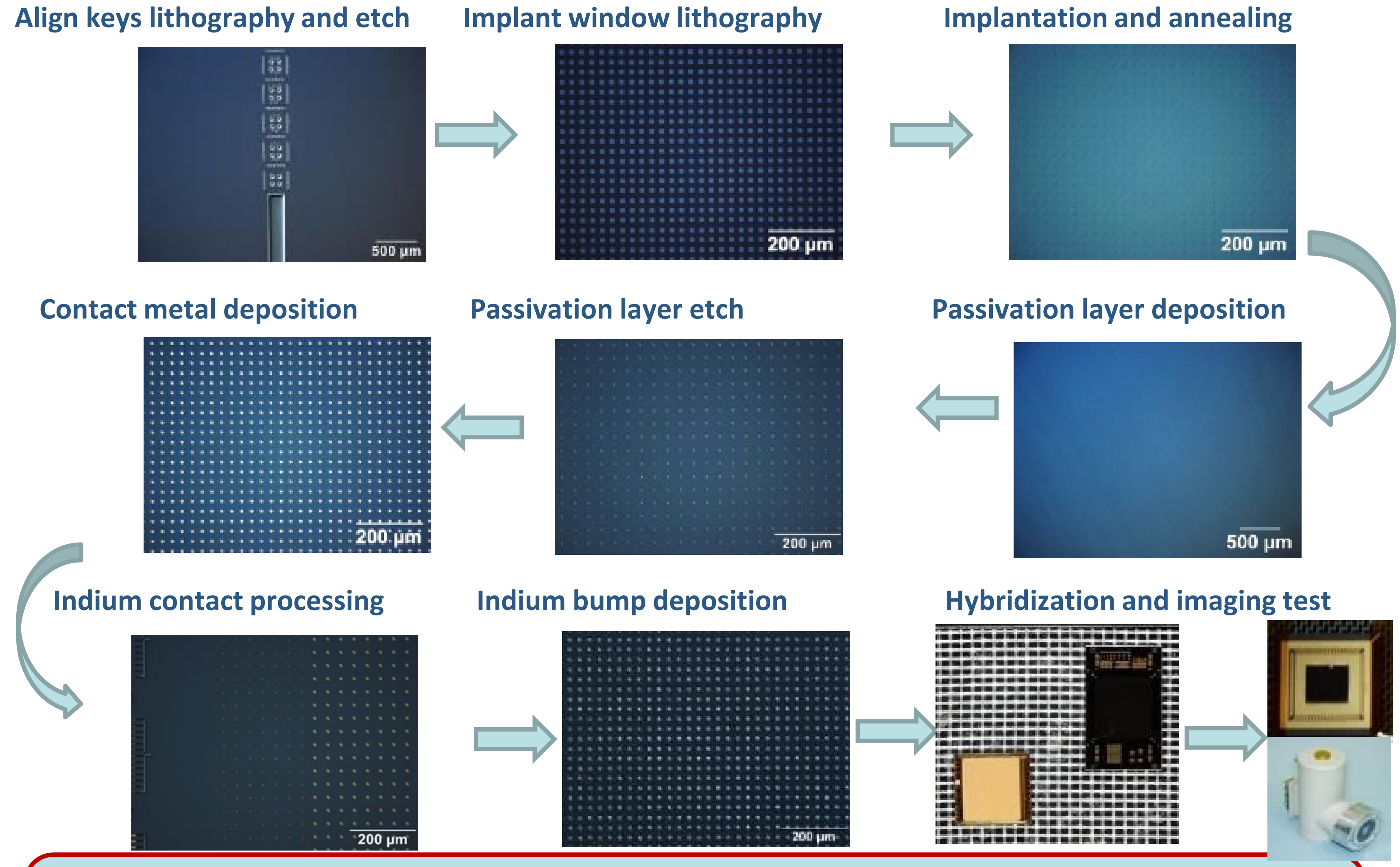
2. Precise composition and doping control (FTIR, Hall, SIMS)
3. Impurity reduction, low background doping
4. Defect reduction (EPD, surface defect counting, HRXRD)
5. Long carrier recombination lifetime (μs level) hence with long diffusion length

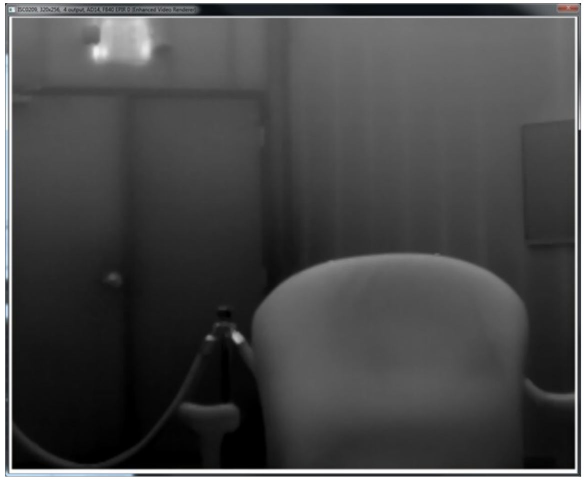


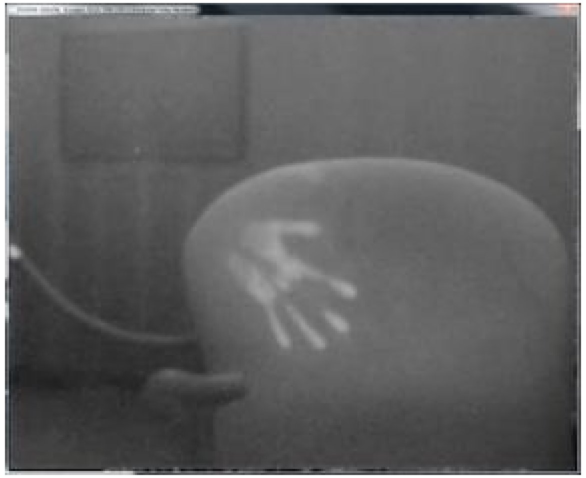


- MBE growth of high-quality HgCdTe layers achieved.
- Material tested under radiation flux.

Device Fabrication – Standard Process



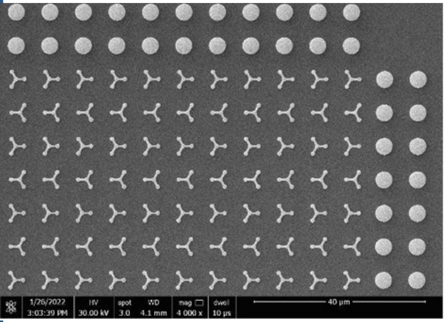


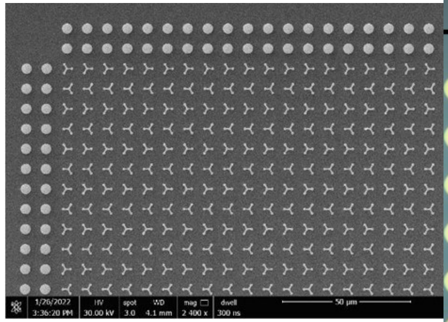


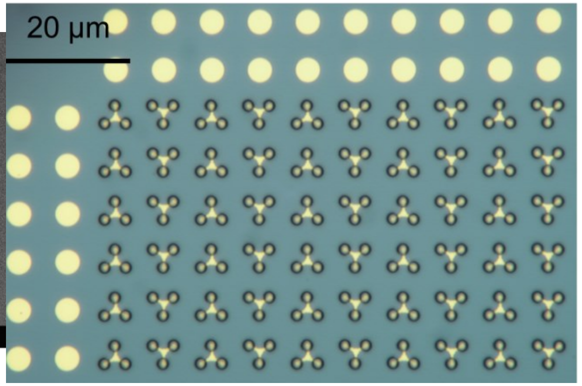
- EPIR optimized process control for array fabrication
- Background limited dark current performance achieved

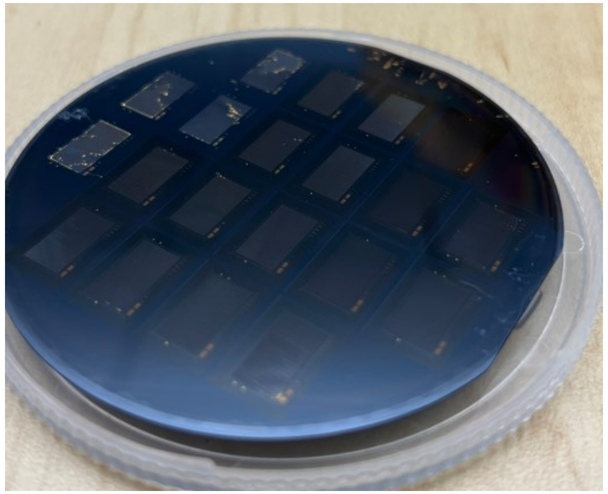
Fabricated FPA with Subpixels for Improved RadHard

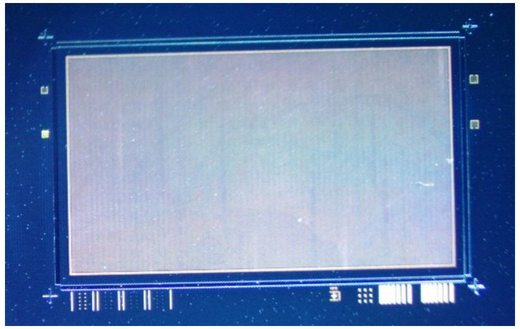
Before indium bump deposition



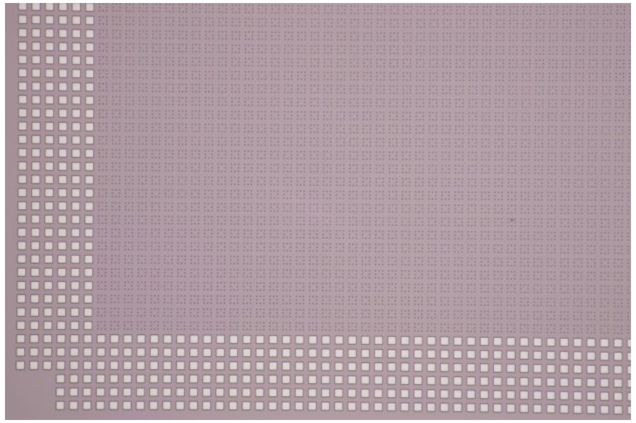


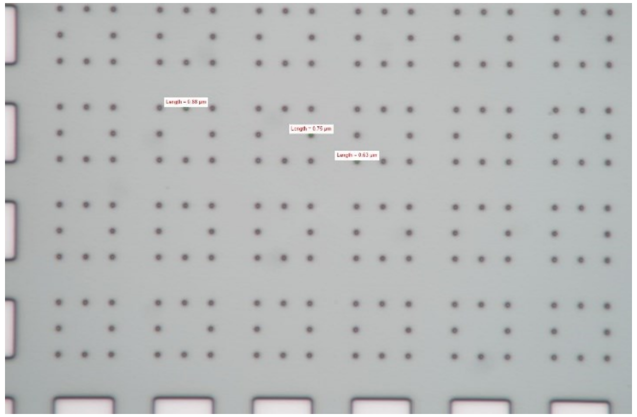


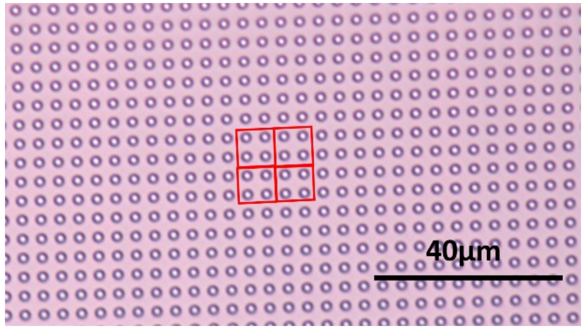




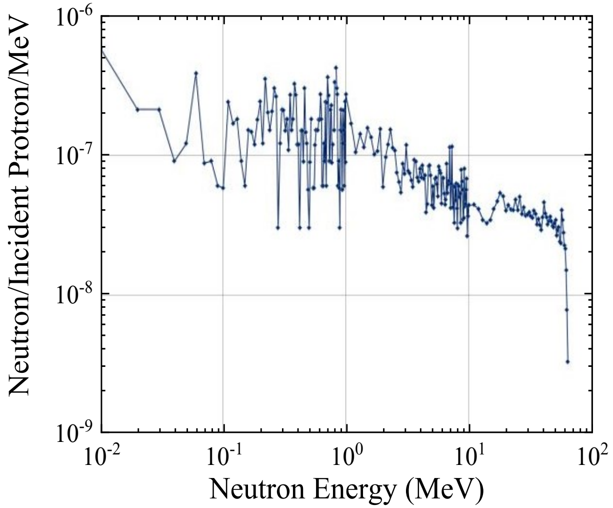
Common contact deposited after activation annealing

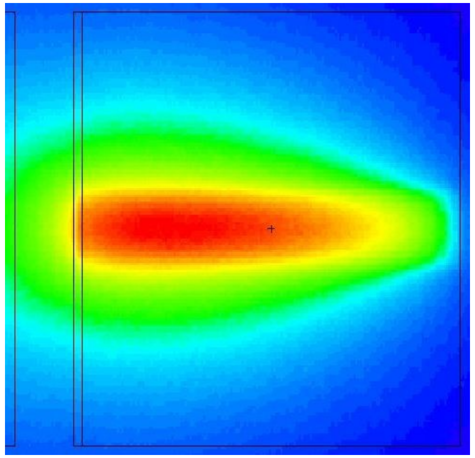


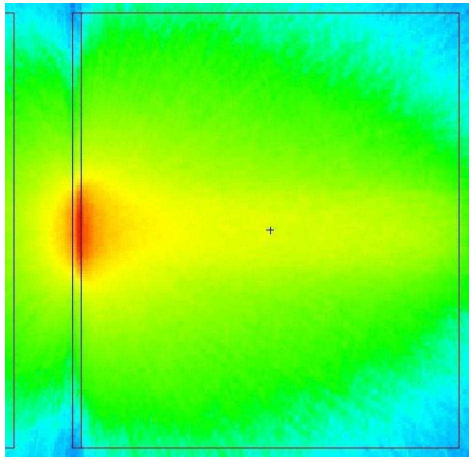


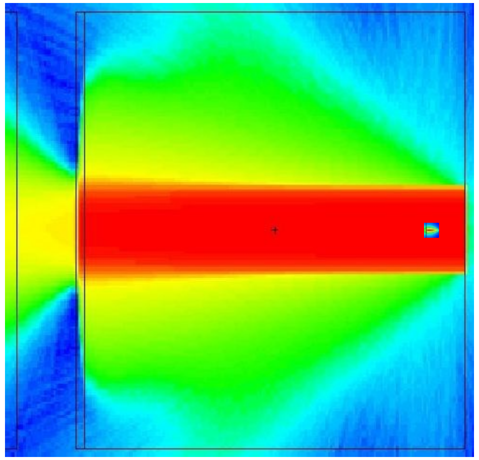


Neutron Exposure Test

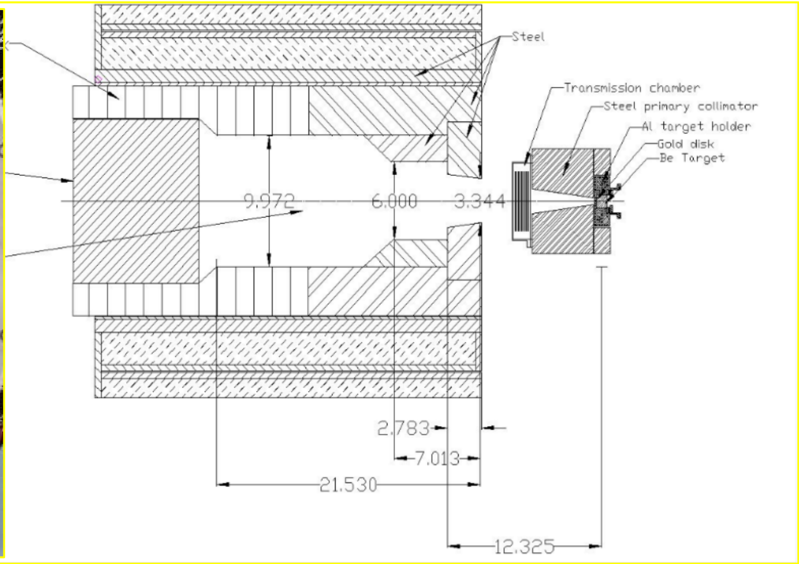


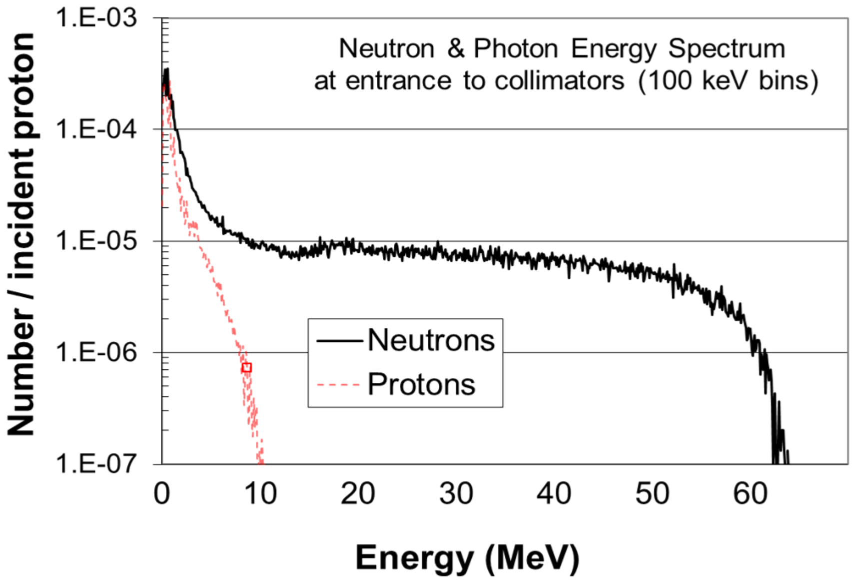






Proton Photon Neutron

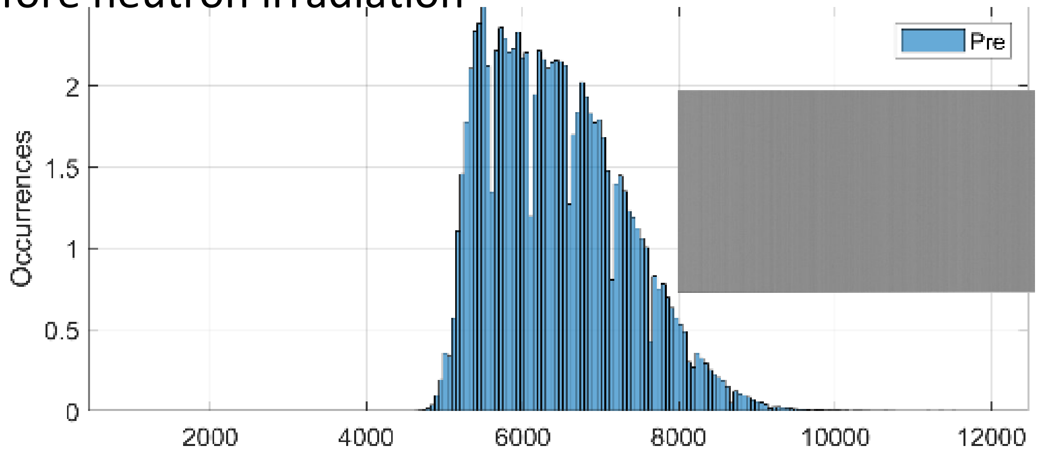


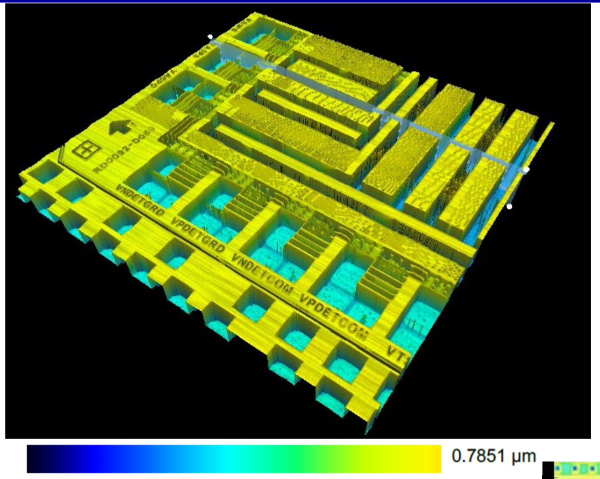


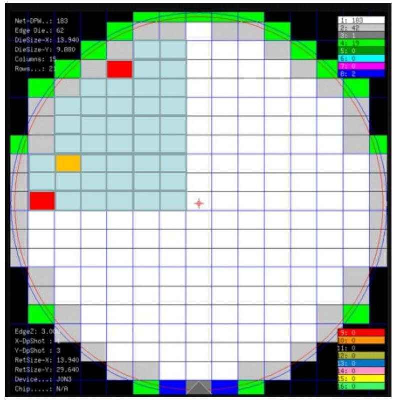
Choice of ROIC

- Senseeker's ROIC and ROIC mounted on PCB were tested under >1×10 ^{9} n/cm^{2}/s (up to 2×10 ^{9} n/cm^{2}/s) neutron irradiation for 2 hours

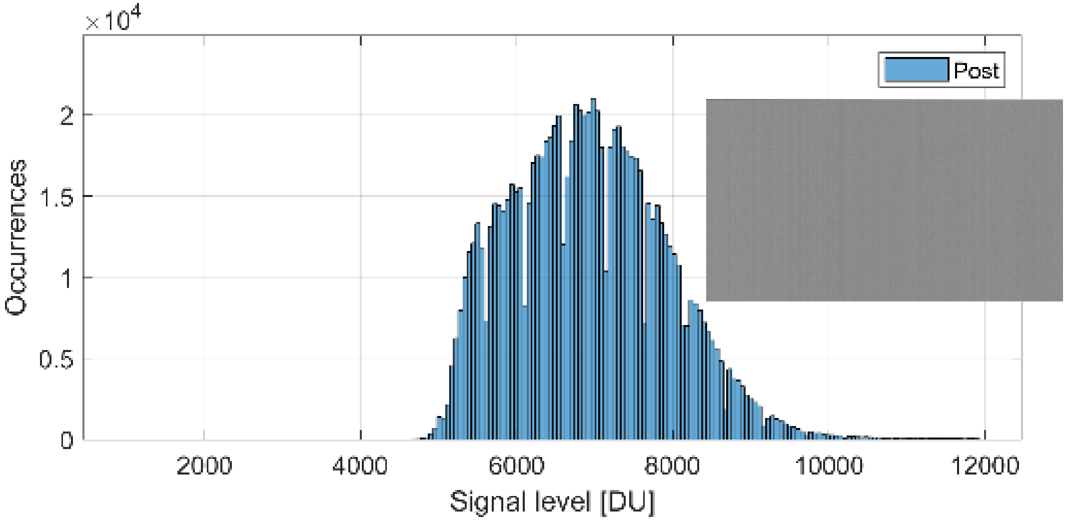
Before neutron irradiation



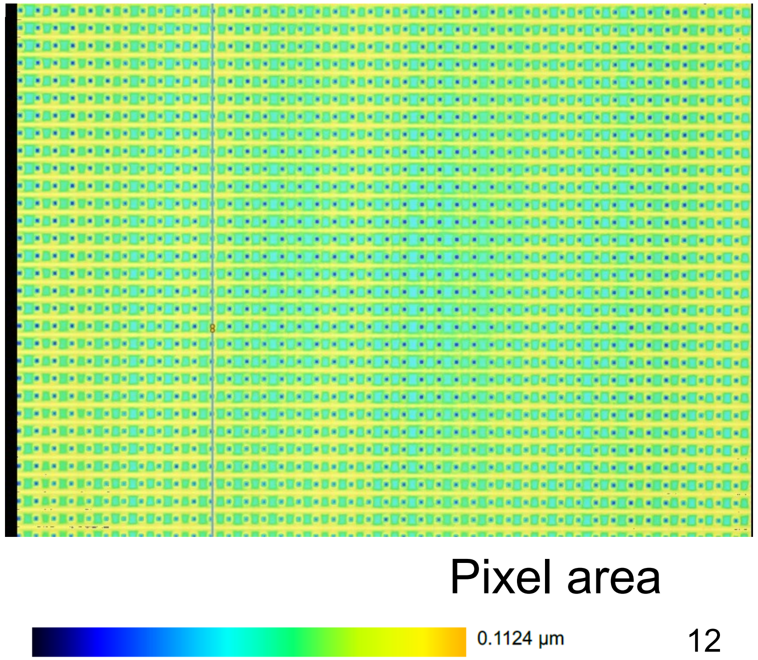




after neutron irradiation

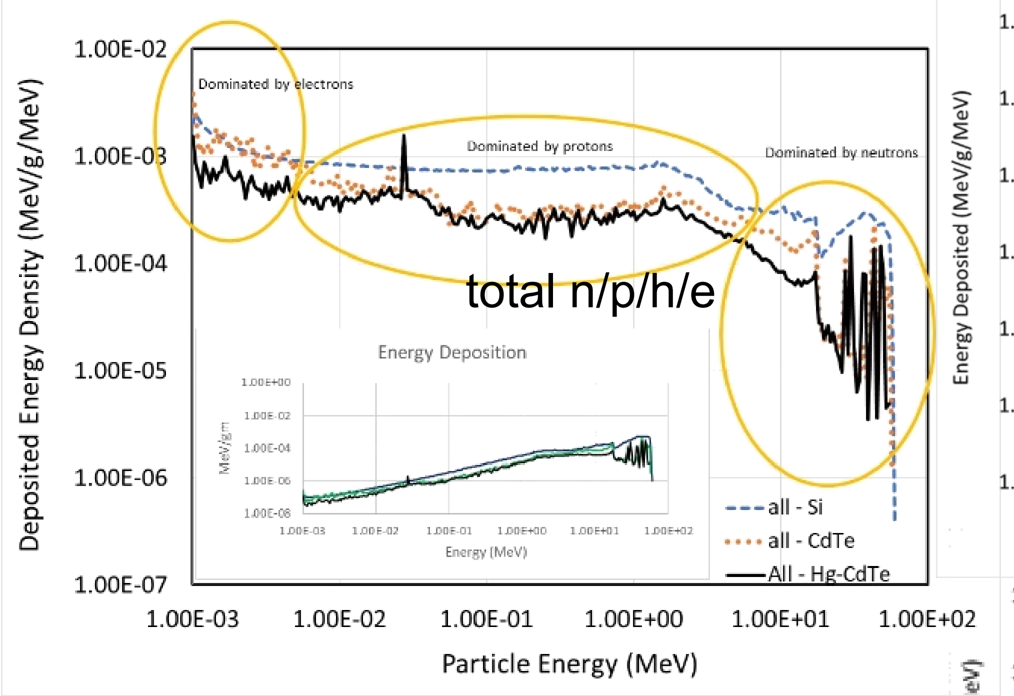


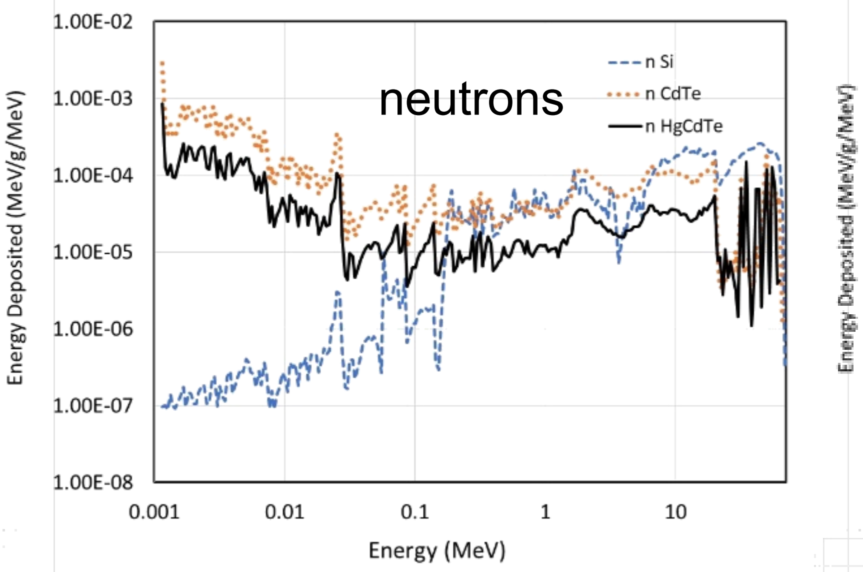
- No significant performance degeneration was observed after neutron exposure
- ROIC was purchased in wafer scale
- FPAs were fabricated using Senseeker's footprint design

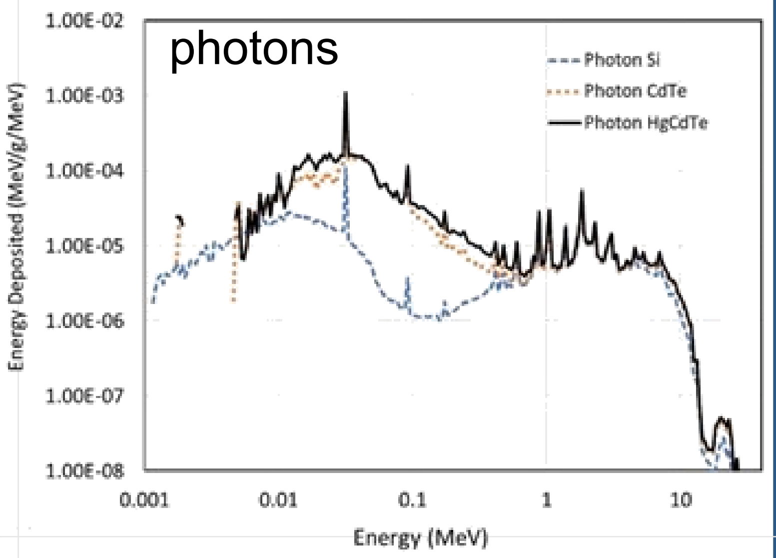


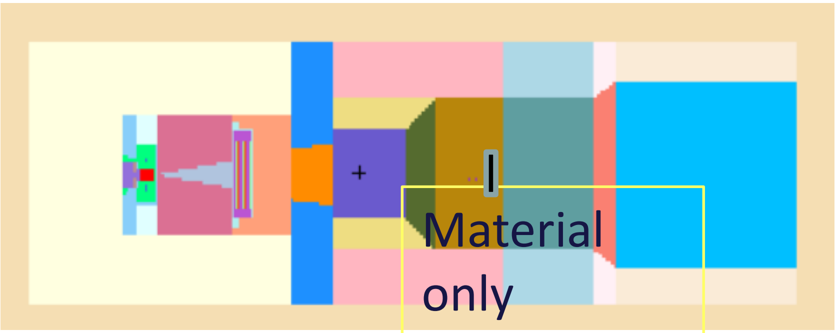
Pixel area

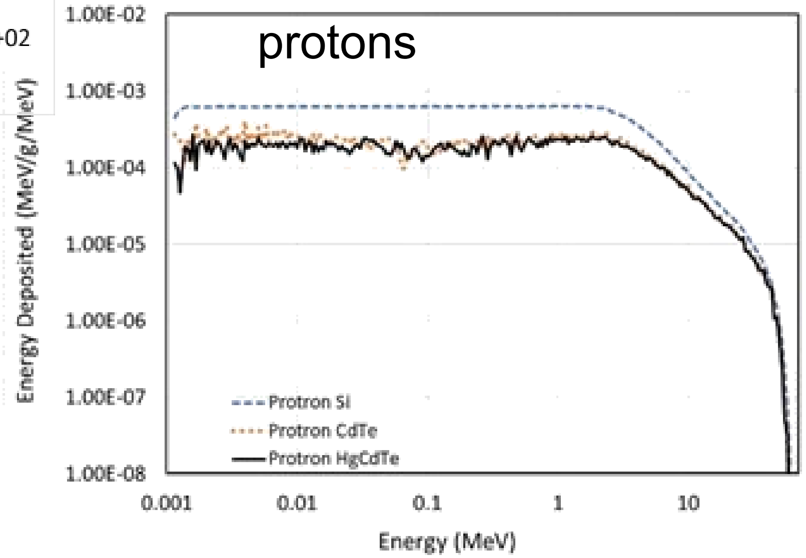
Energy Deposition in Material: MCNP Calculation at FNAL

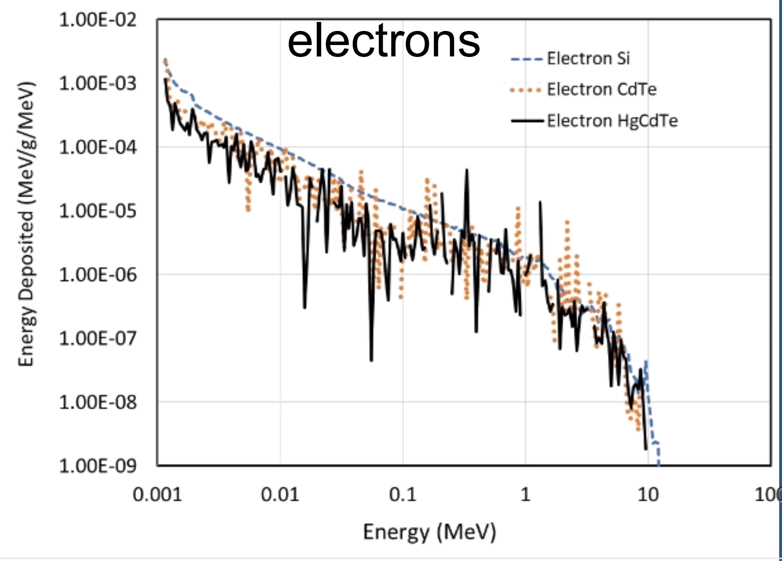






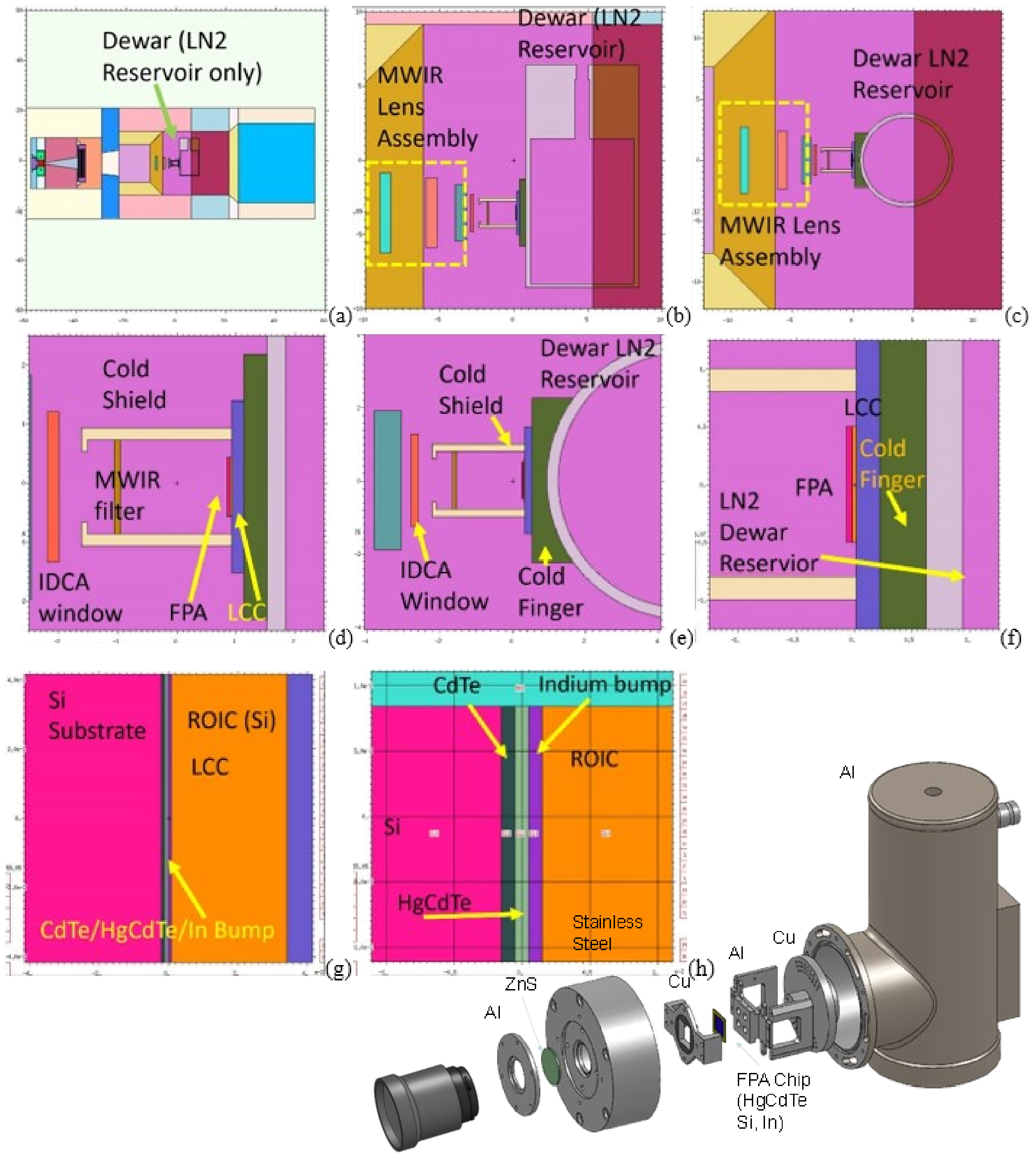




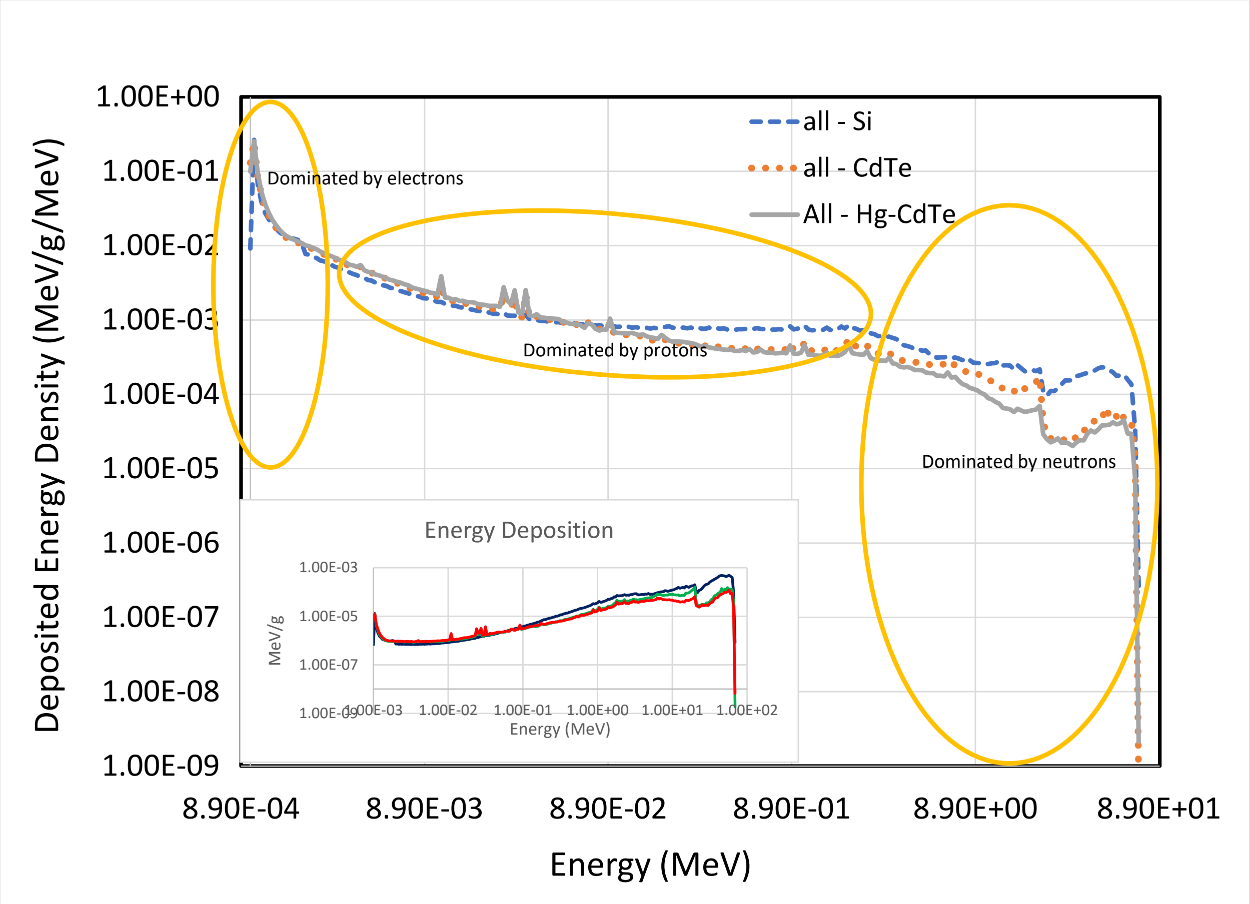


Deposited energy on HgCdTe FPA: through all electron, photon, proton and neutron mechanisms

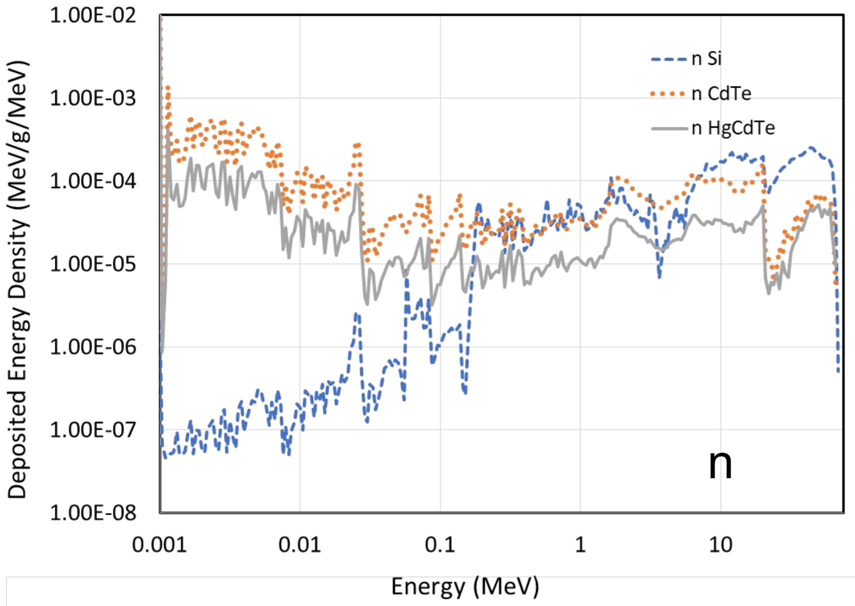
MCNP Camera Modeling by Adapting FNAL's Code

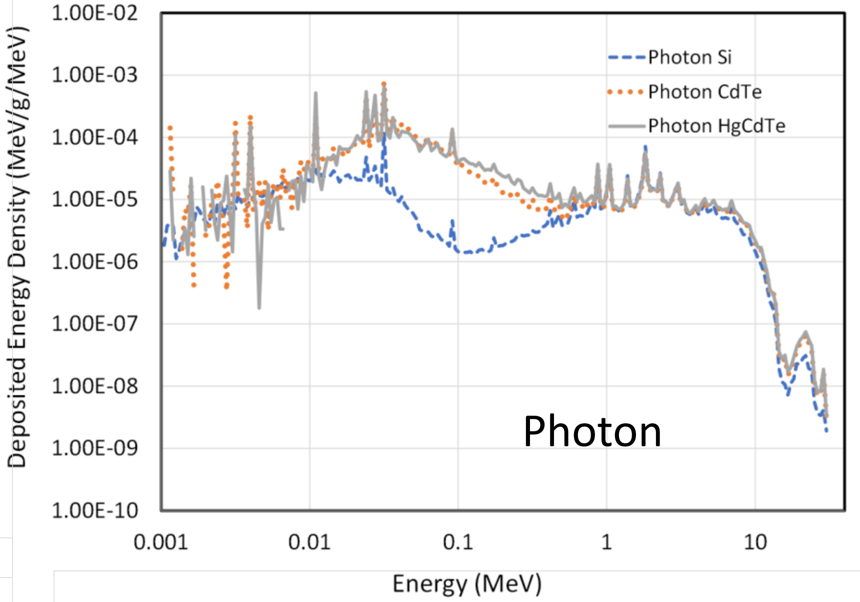


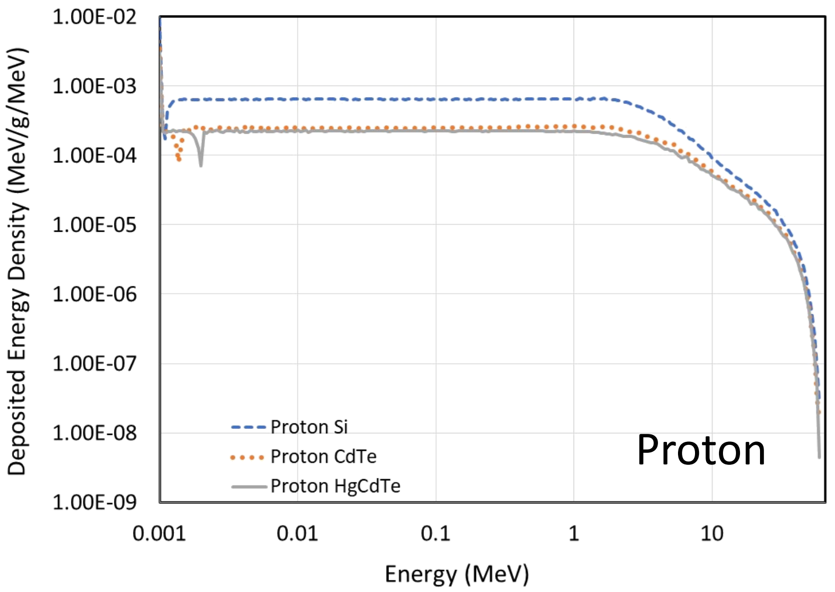
- Energy density deposited (F6 Tally) in the FPA chip.
- Include energy deposited in Si, CdTe and HgCdTe

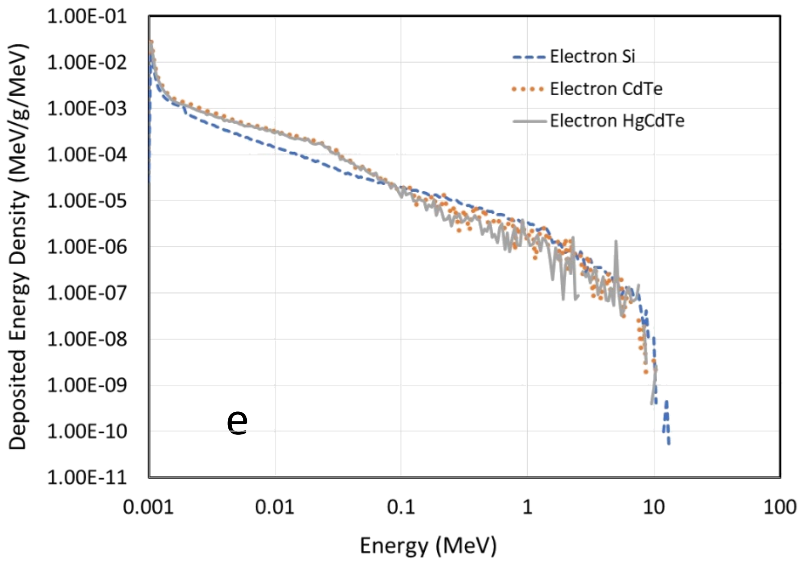


MCNP Camera Modeling



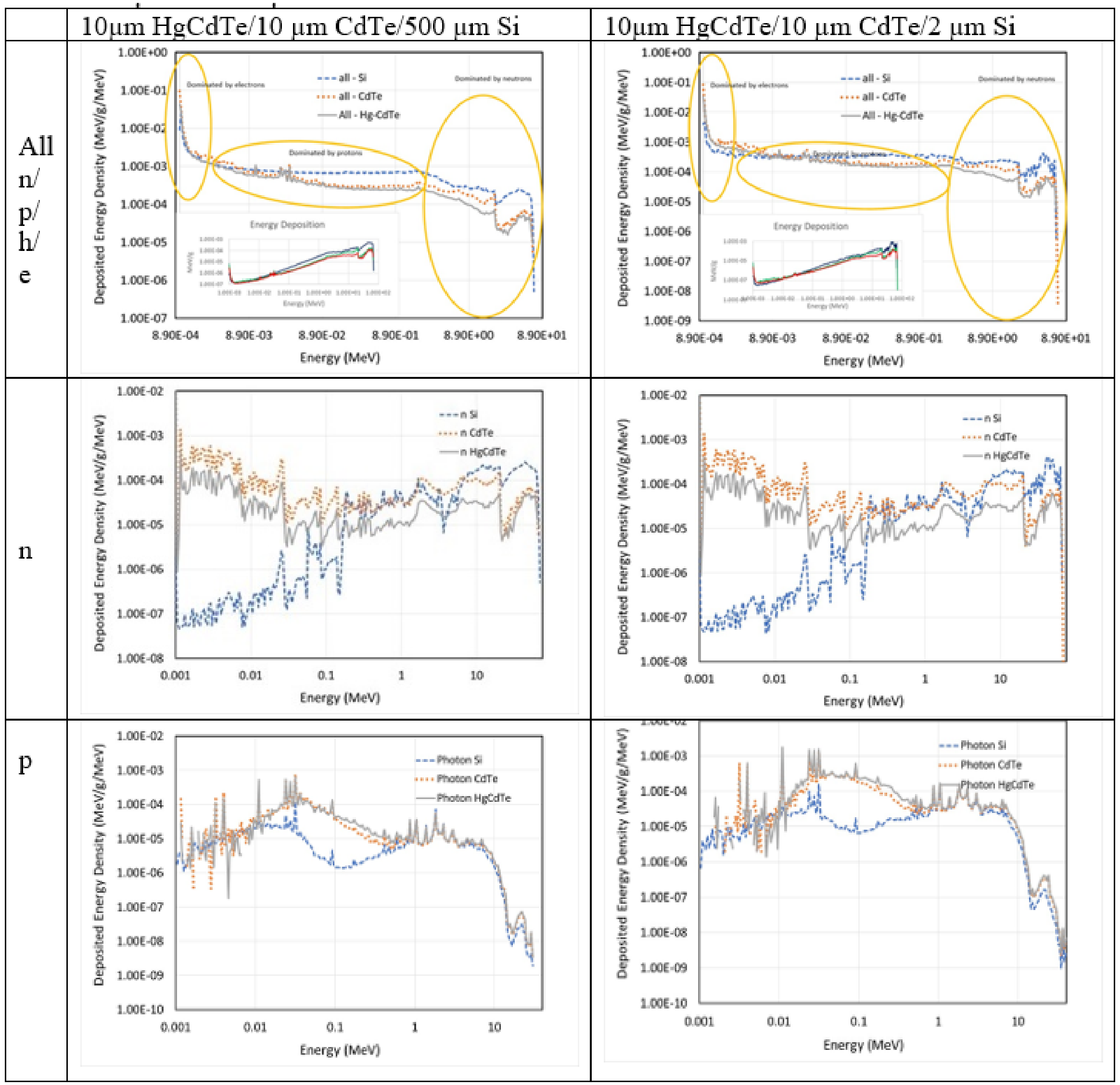


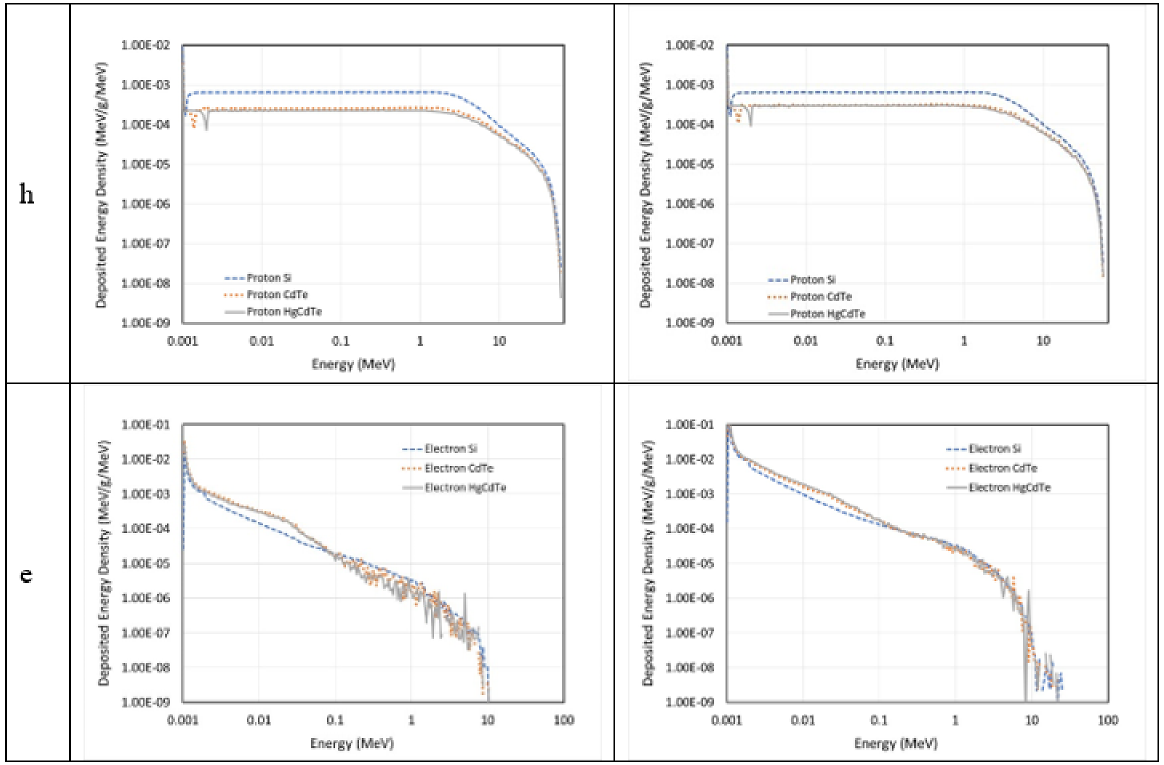




- Energy density deposited (F6 Tally) in the FPA chip simulated using MCNP.
- Damage to semiconductor chip may not necessarily stem from neutrons during neutron exposure.
- All 4 mechanisms including neutron, high energy photon, proton and electron contributed to the energy deposition into FPA sample

Effect of Thinning Si Substrate



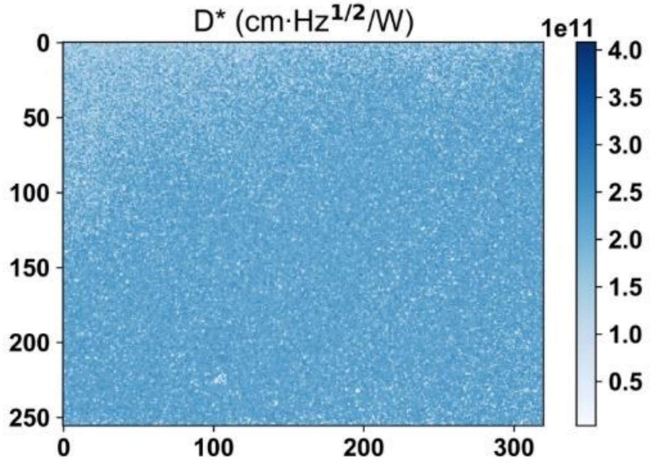


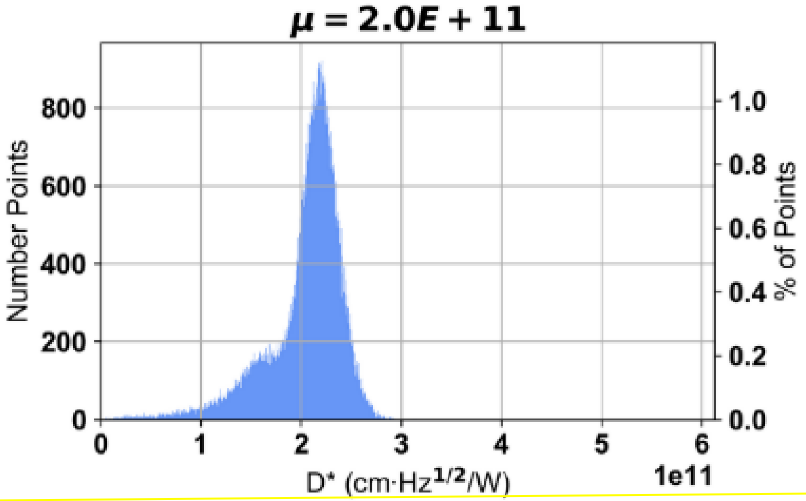
- Almost identical behavior with normalized mass.
- Thin substrate samples have less energy deposited directly through neutrons while more energy through h/p/e, especially through e with energy less than 10keV.
- Low energy electrons deposited in Si. Si may have less influence on HgCdTe FPAs as long as a proper grounding is present.

NEDT/Detectivity Before and After Neutron Flux Exposure (~10^{12} n/cm^2)

EPIR

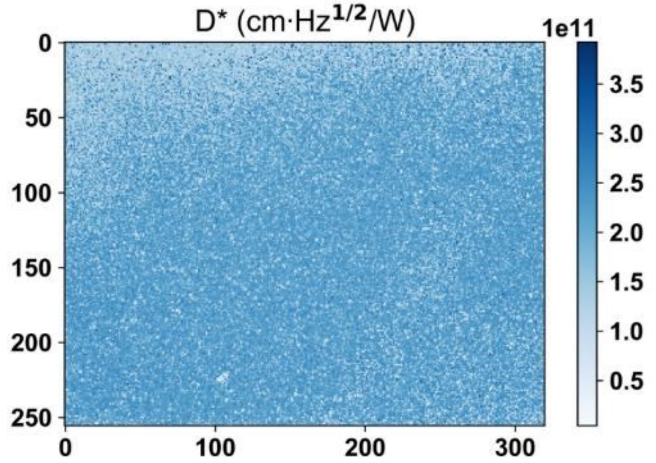
Before Neutron flux

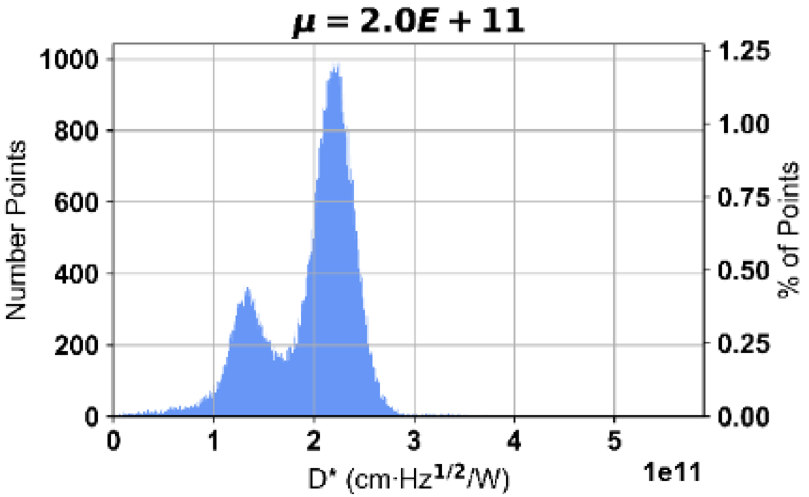




Total doses: ~10^{12} n/cm^2, Corresponding to 10^5 n/cm^2s, 1/3 year, 24hrs continuous exposure.

After Neutron flux





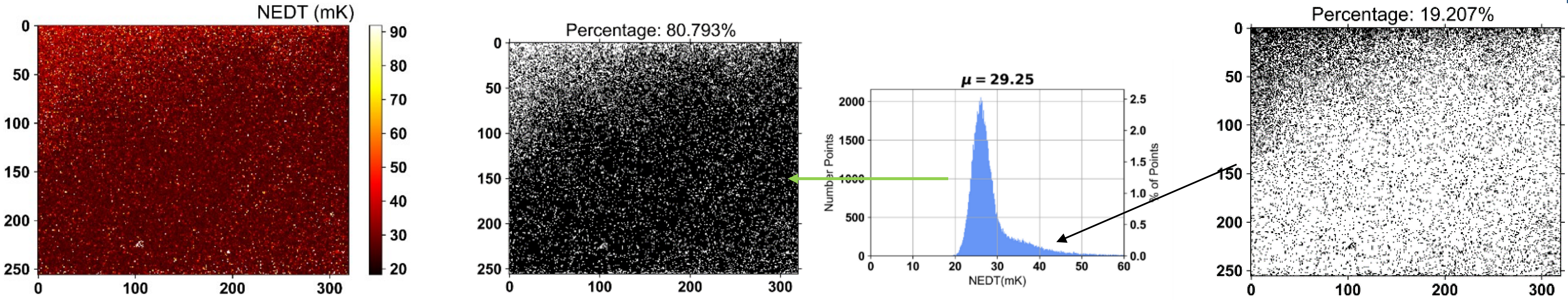
- Median D* was not changed
- Pixel numbers with high noise (lower D*) tail side increased and was split into a separate peak.

NEDT/Detectivity Before and After Neutron Flux Exposure (~10^{12} n/cm^2)

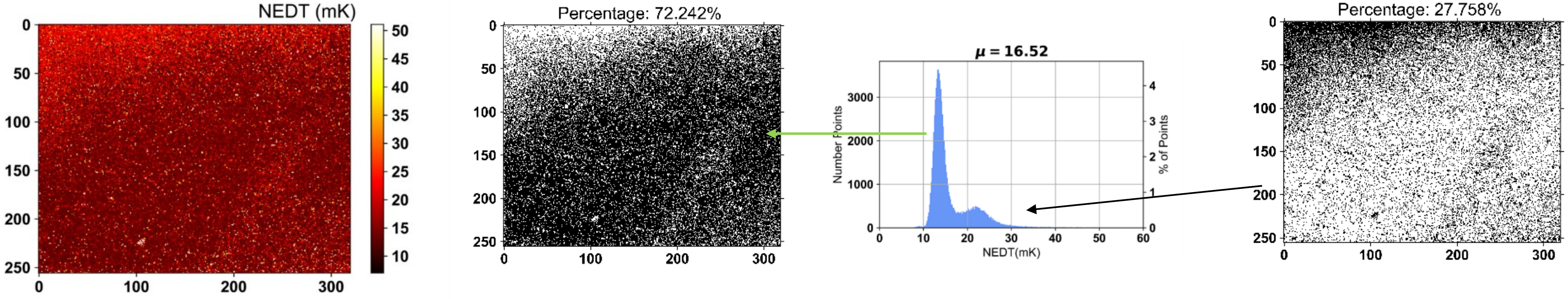
EPIR

Before Neutron flux

Total: ~10^{12} n/cm^2, 10^5 n/cm^{2}s, 1/3 year, 24hr continuous exposure

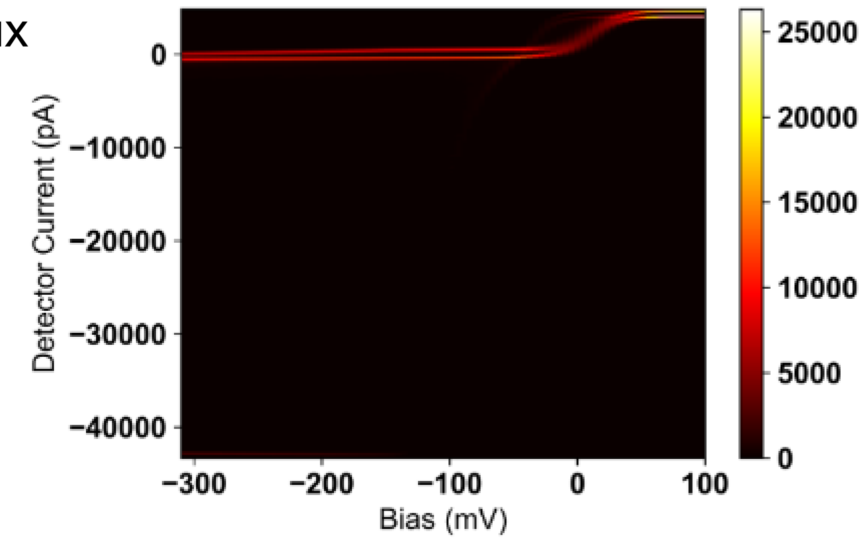


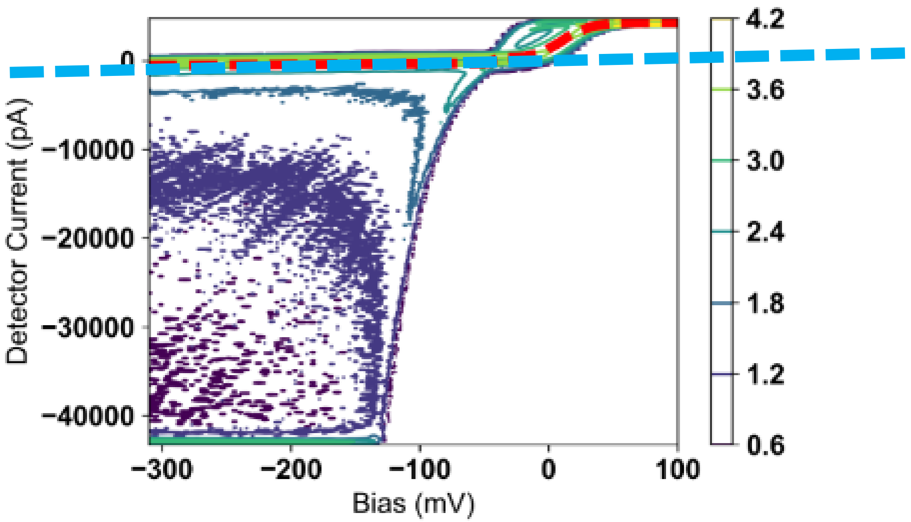
After Neutron flux



I-V Characterization of FPA Before and After Neutron Exposure

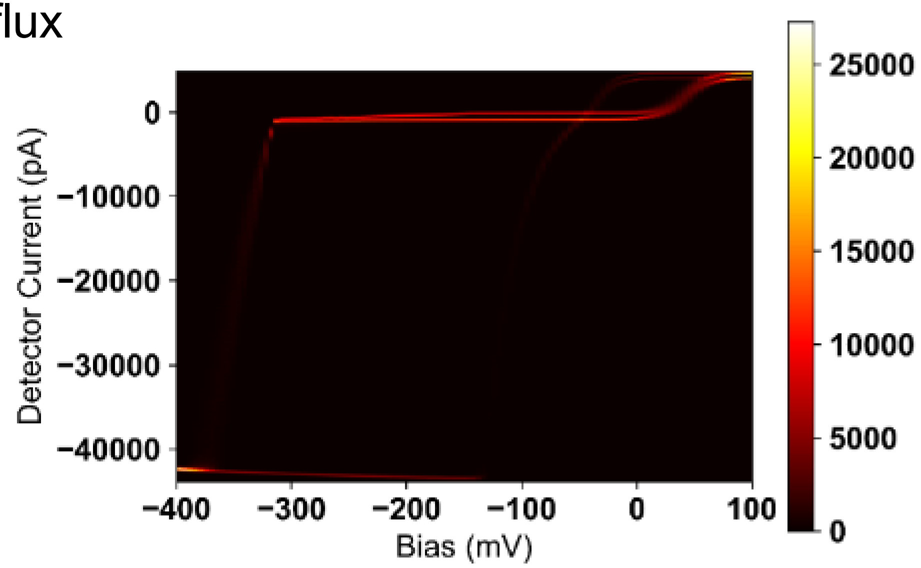
Before neutron flux

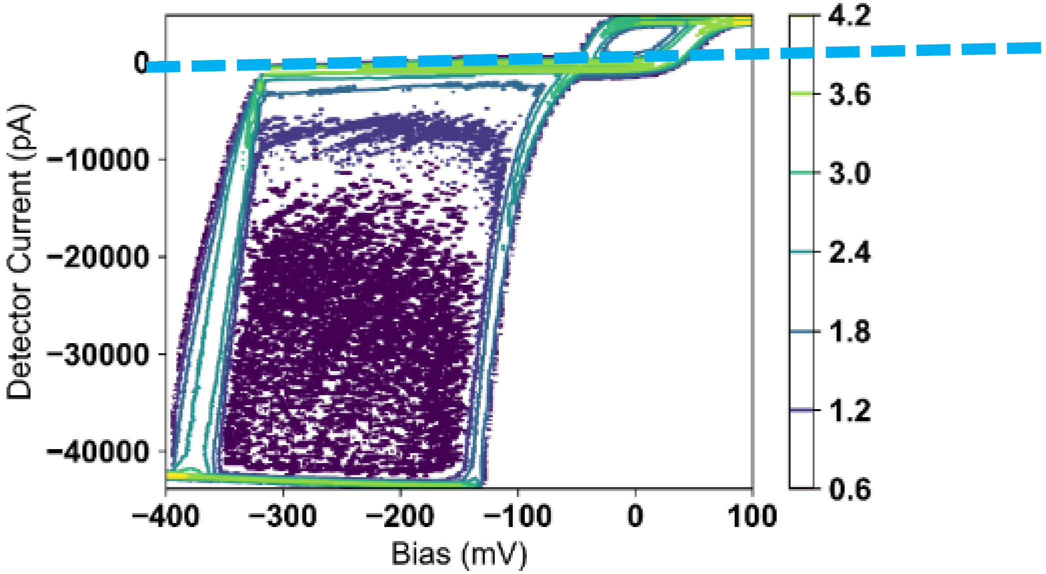




After neutron flux

Total: ~10^{12} n/cm^2

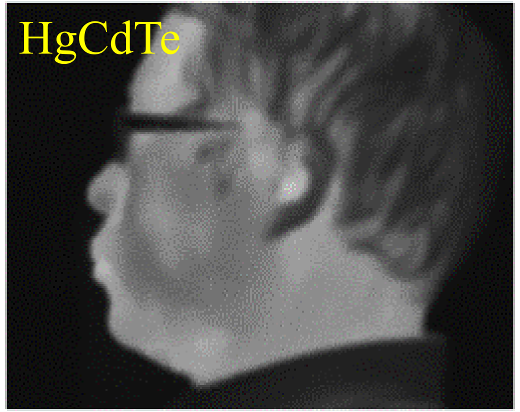


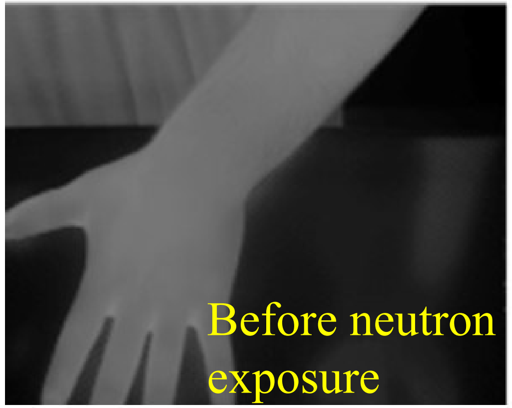


Imaging with EPIR-Assembled IR Cameras

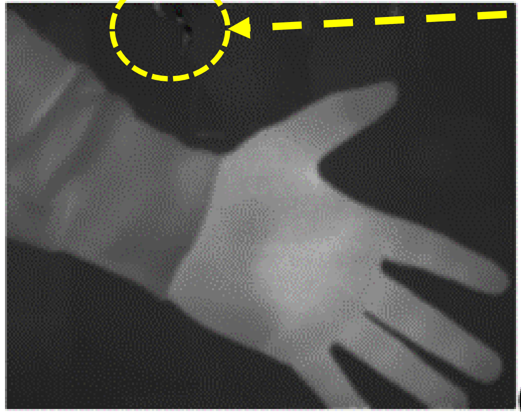
3-5µm MWIR

After 10^{12} n/cm^2 neutron exposure

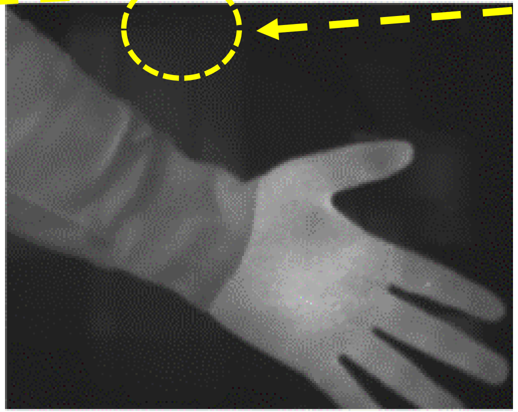




after 1.5×10^{13} n·cm^{-2} neutron exposure under an instant flux of 2×10^{9} n ·cm^{-2} ·s^{-1}



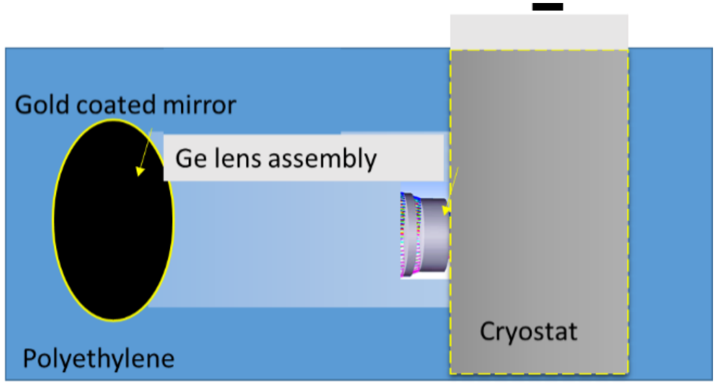
after an extra temperature cycling from 100K to room temperature

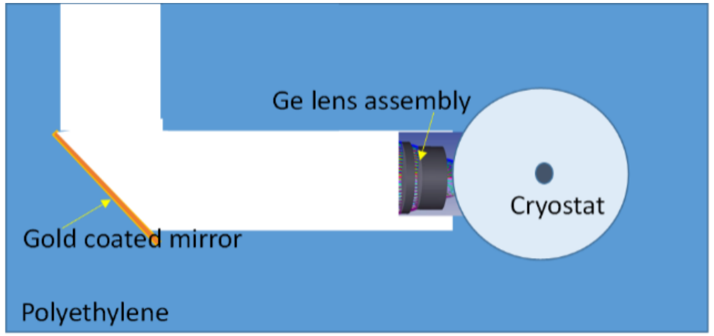


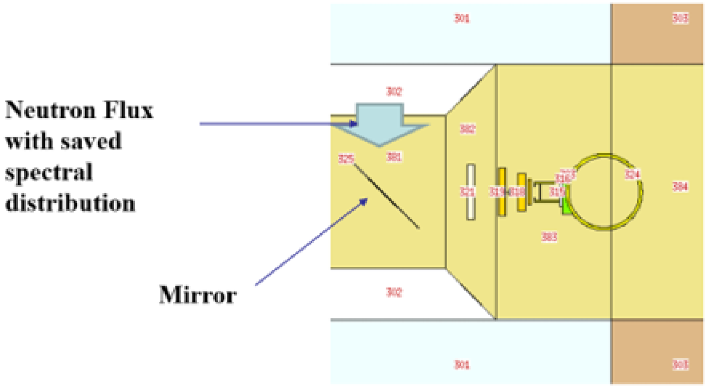
The circled area shows the defective pixels recovered after temperature circling.

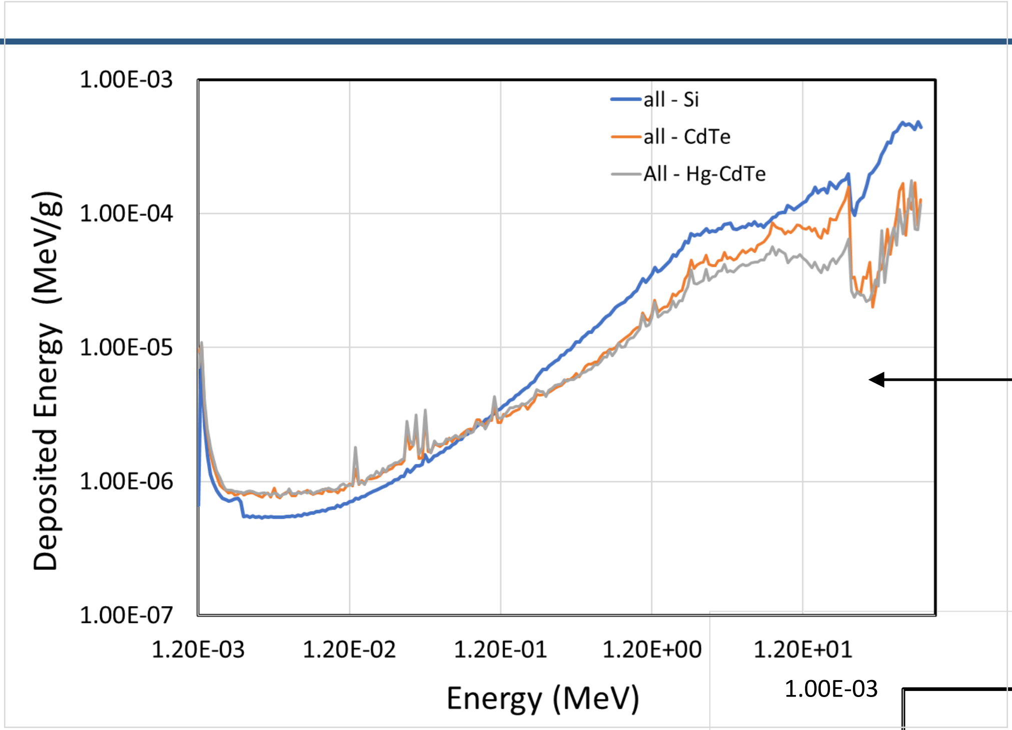
Our T2SL nBn FPAs also shows good functionality, however Sb decay emits β particles and the FPA required ~4 Months "cooling down" period before being released from FNAL's neutron facility

Camera Design



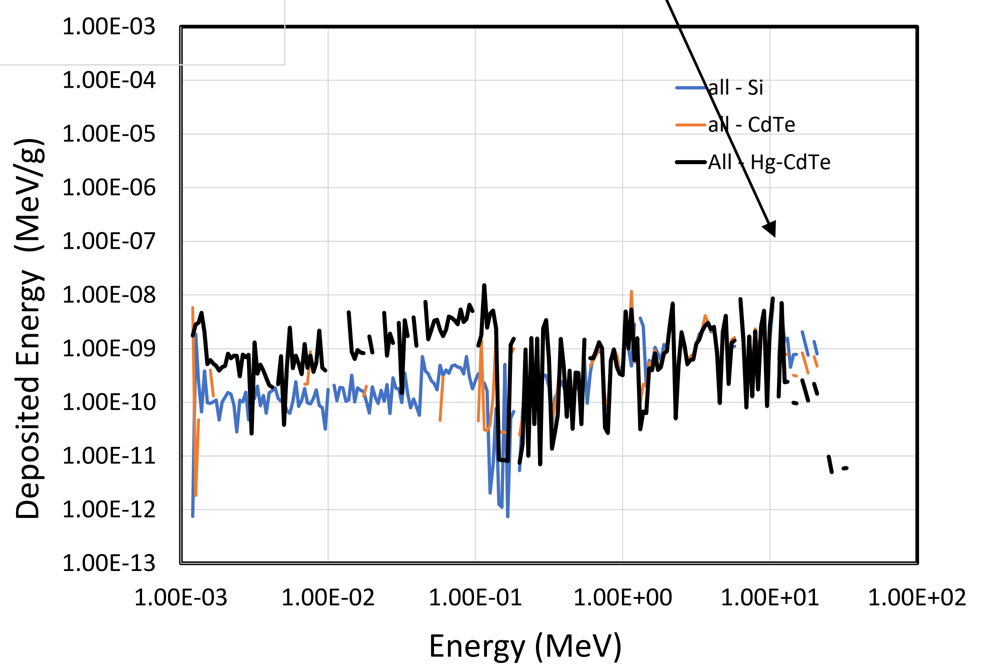




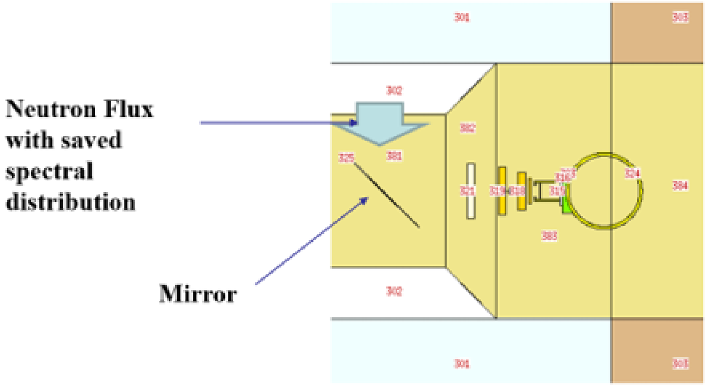


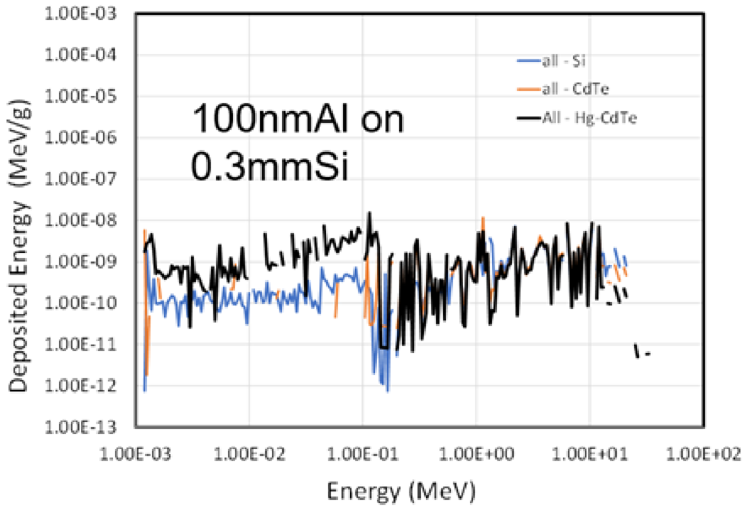
Significant reduction of the energy deposited in FPA by high energy particles

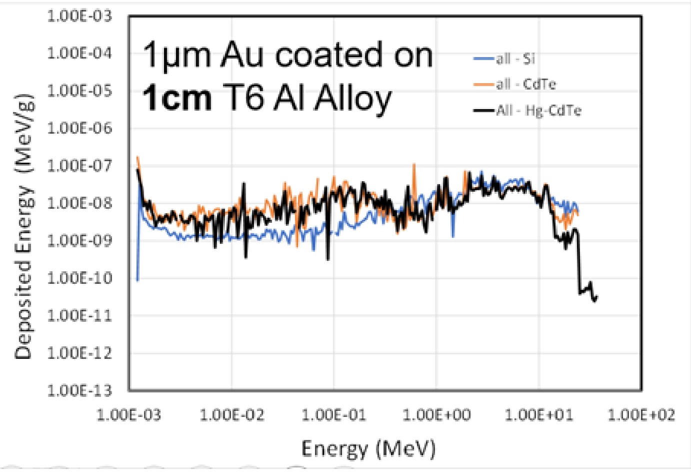
Reflection configuration can significantly protect FPA from damage caused by high energy neutron exposure



Camera Design

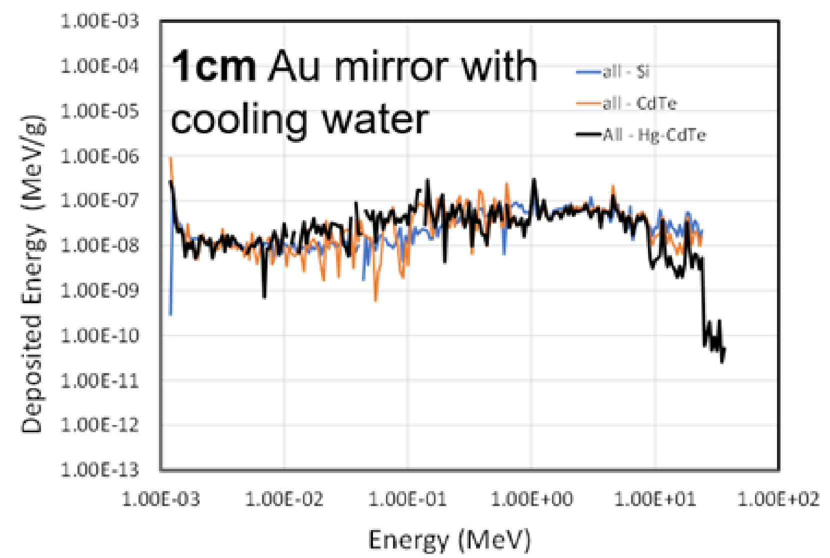


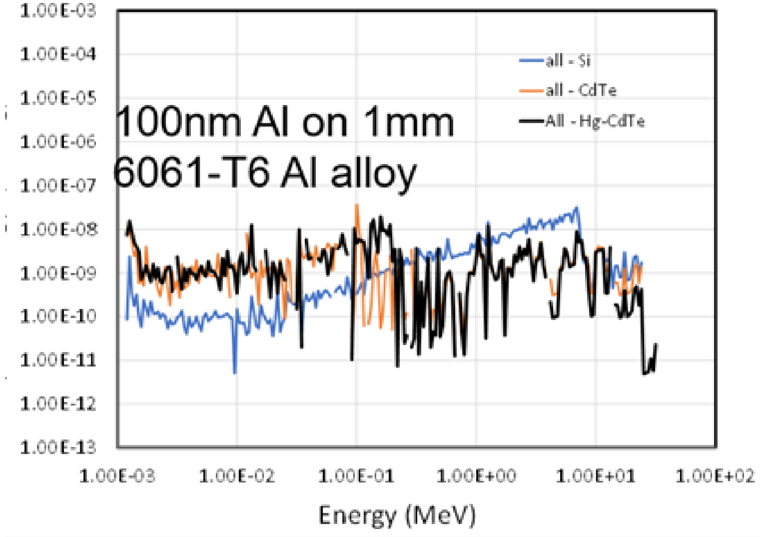




- Various mirror designs were evaluated using MCNP

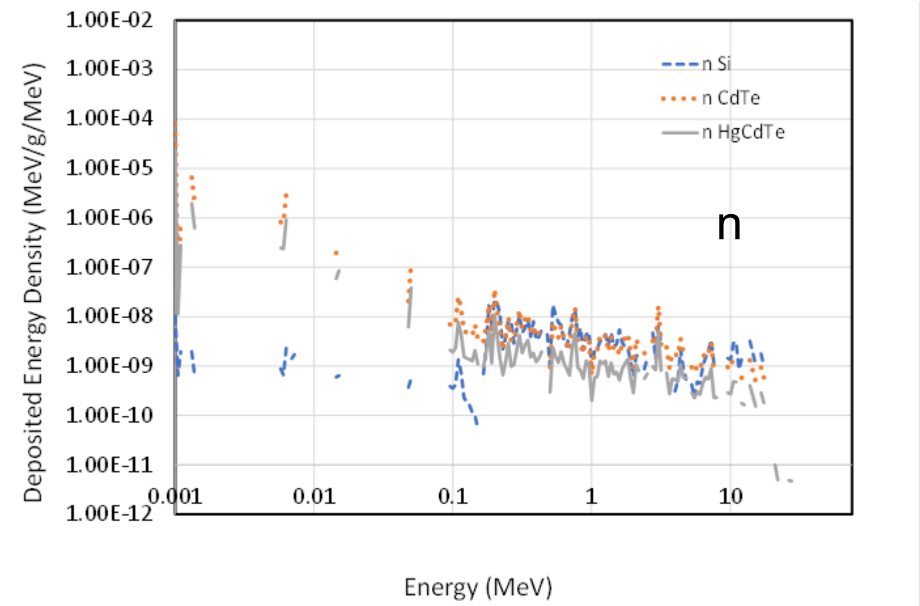
- Si based mirrors show that they introduce less energy deposition to HgCdTe FPA

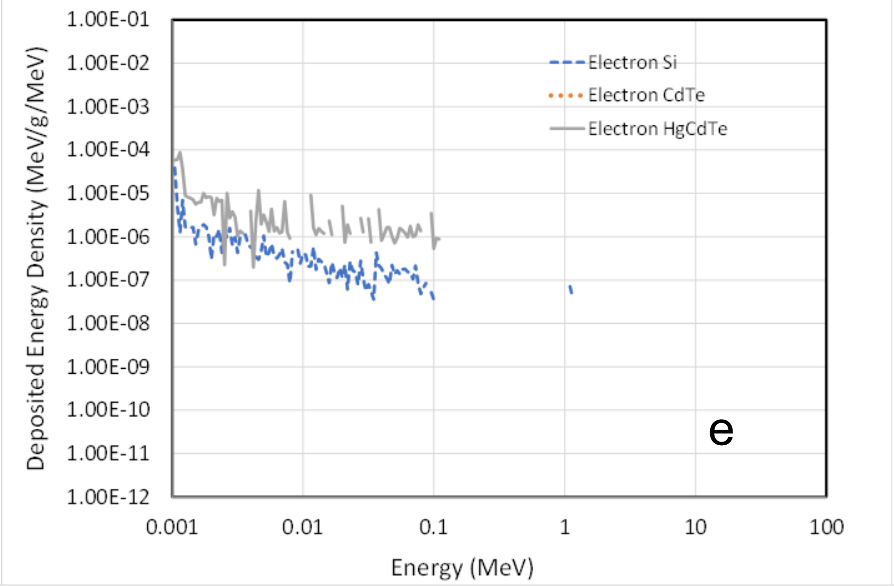


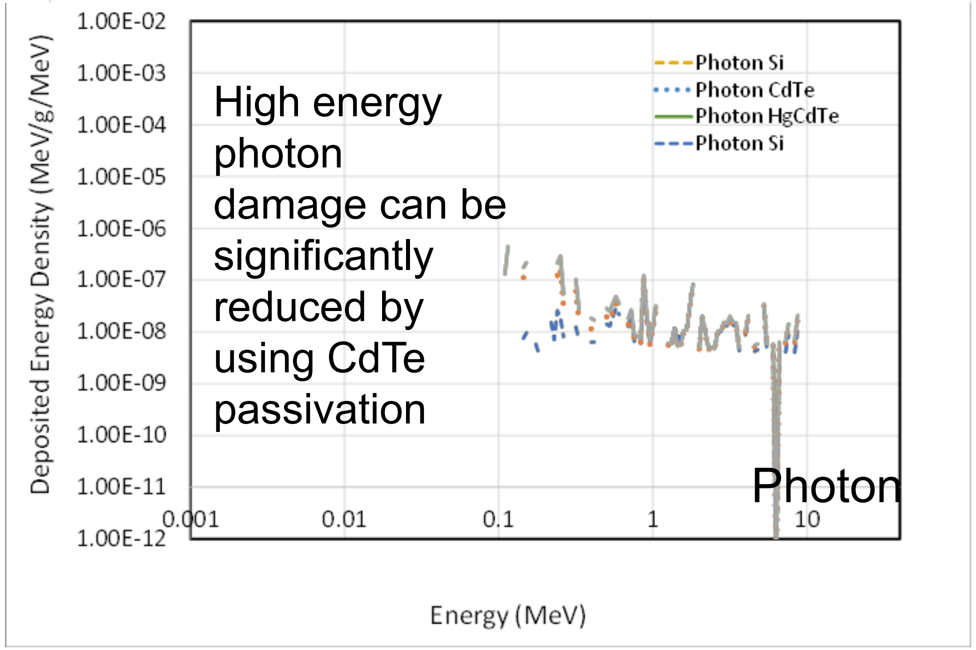


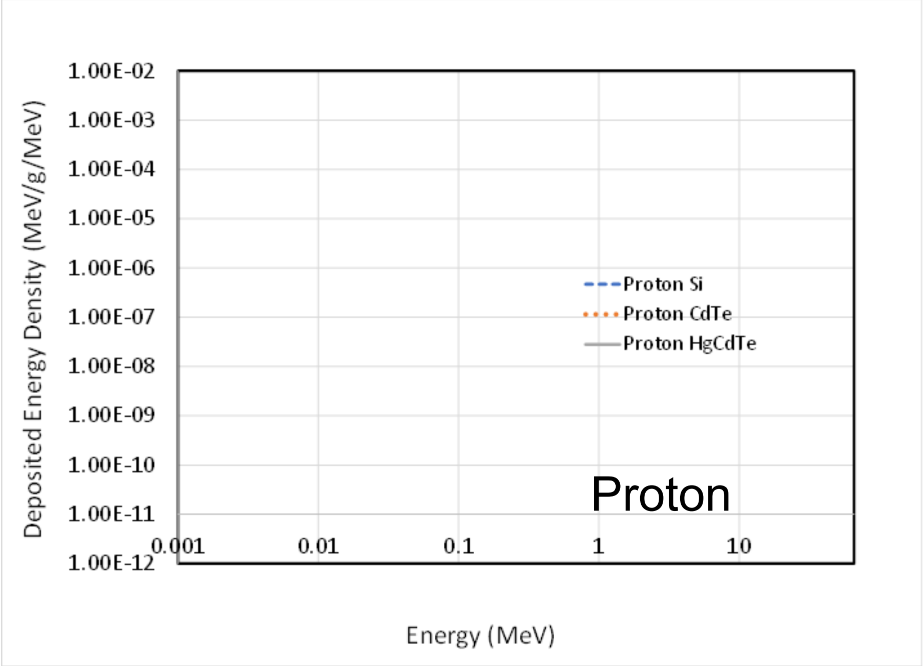
Energy Deposited on FPA After Using Mirror

EPIR



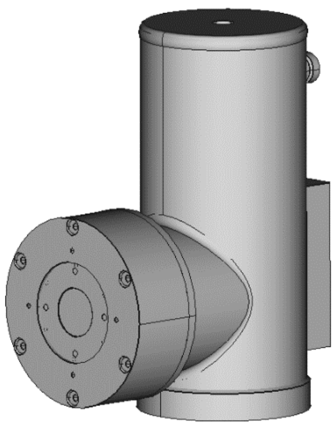


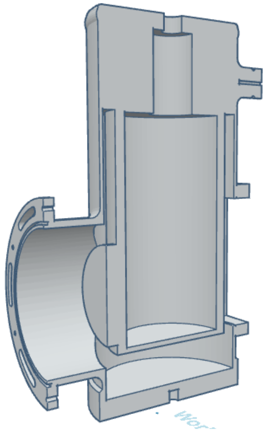


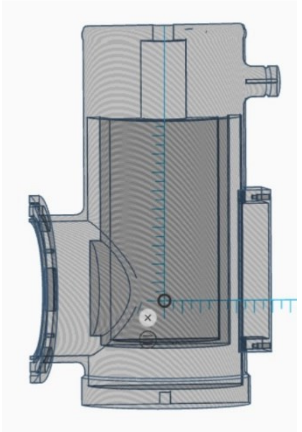


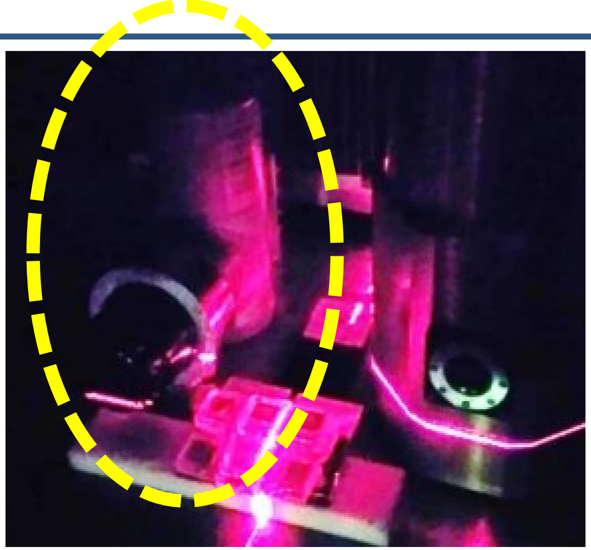
- After using mirror, the energy deposited on FPA through neutron was significantly reduced.
- The energy deposited on FPA through proton mechanism was eliminated
- Less possibility for introducing harmful displacement damage

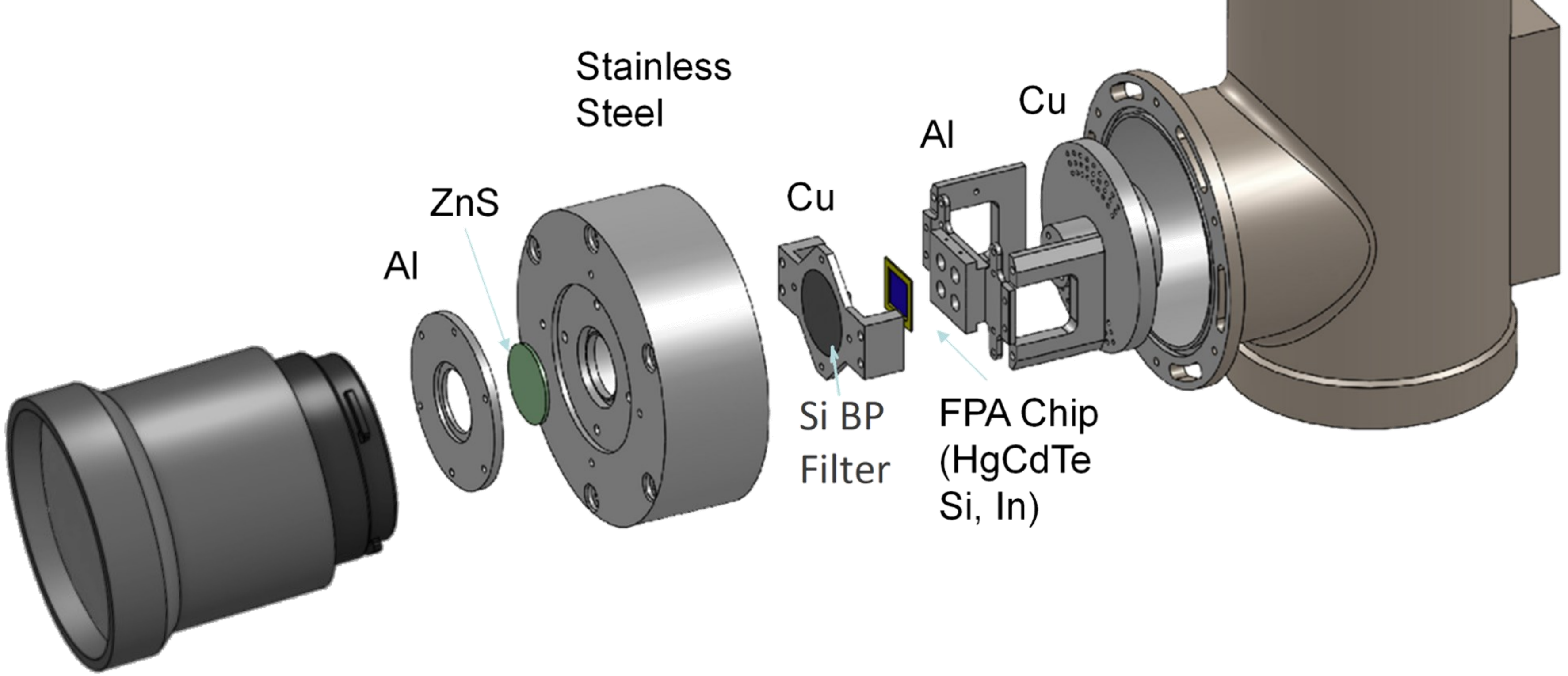
LN2 Cooled Camera Head







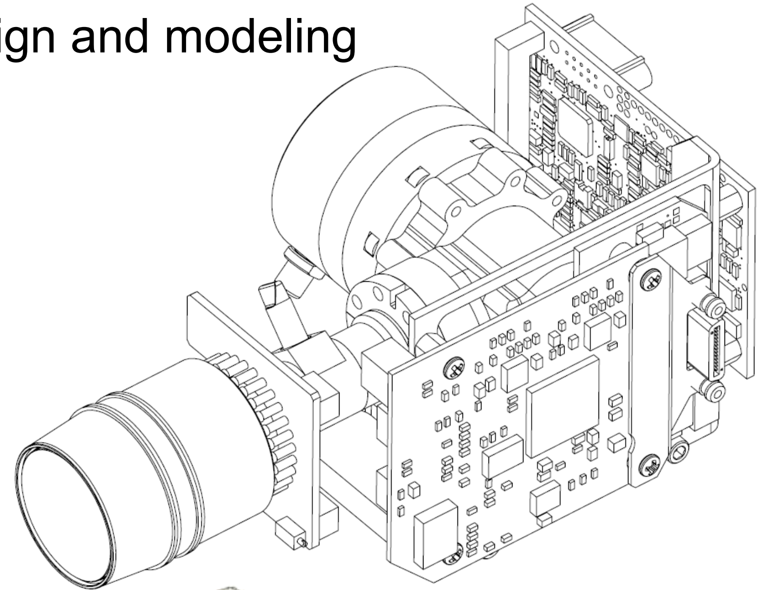


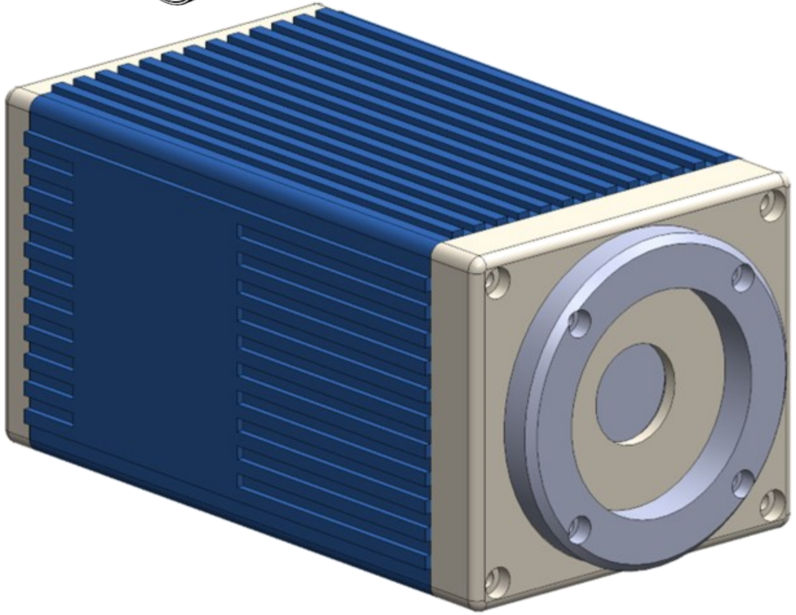


- Already used in FPA testing
- Also tested under **direct** neutron irradiation environment with lenses, filters and ZnS windows (with ARC)

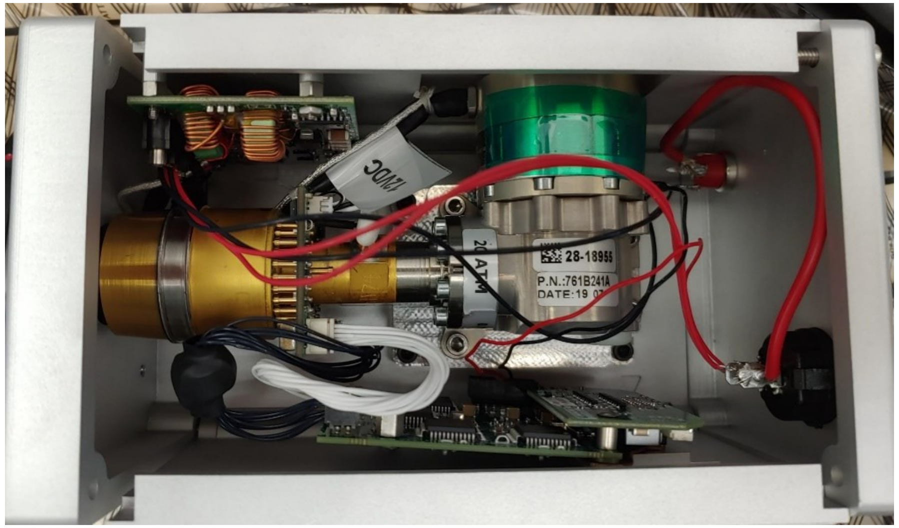
Cameras based on Stirling Cooler (LN2 free)

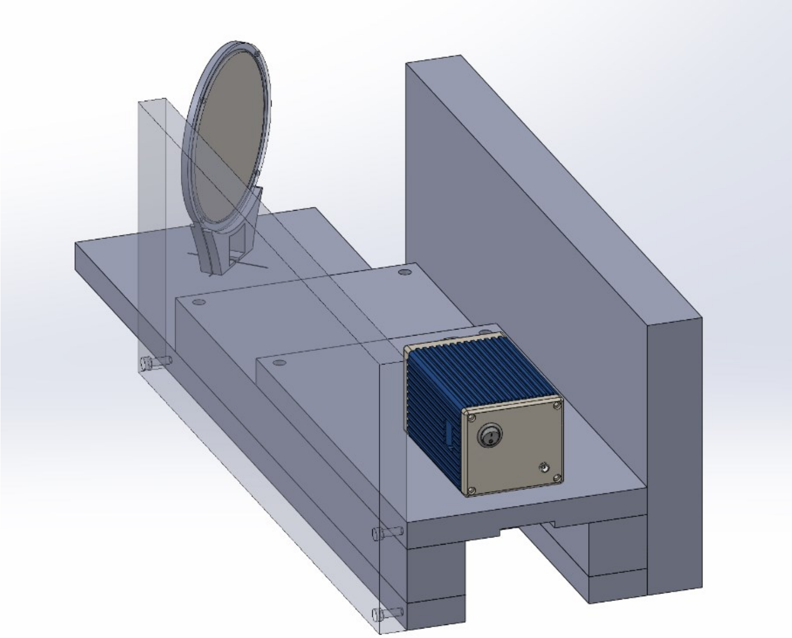
Design and modeling





Assembled camera head

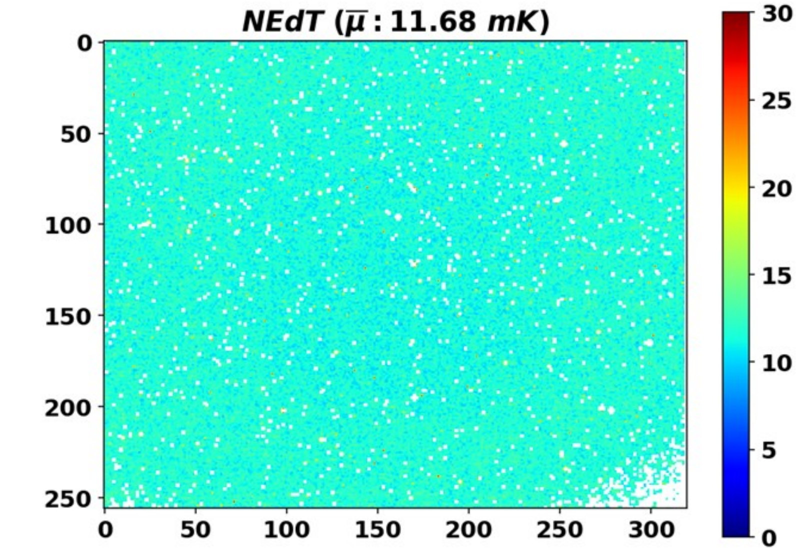


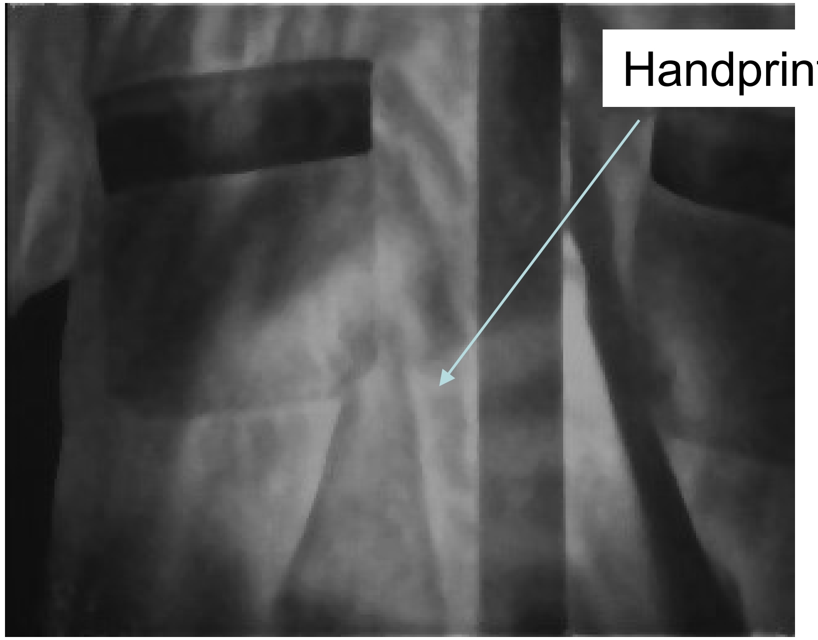


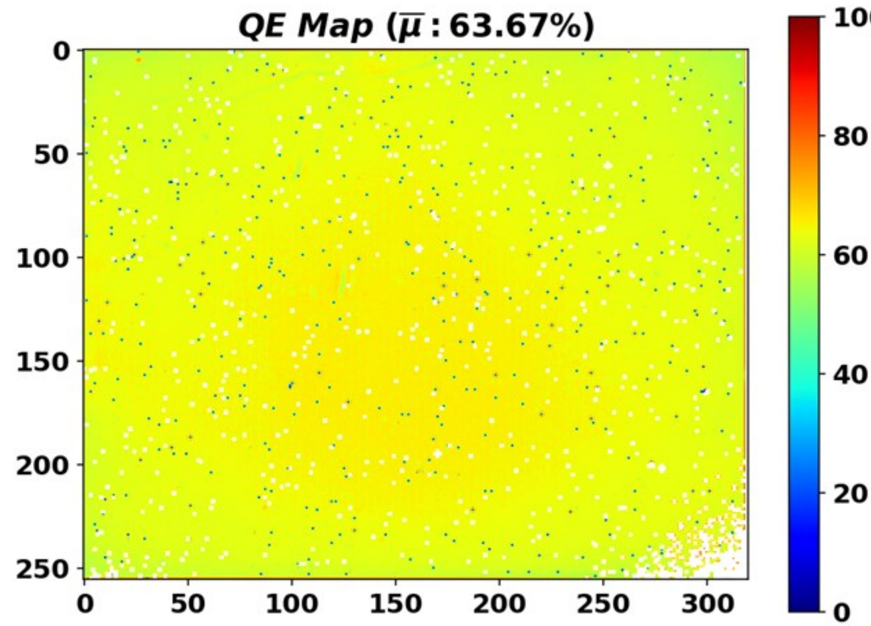
6-inch Si based mirror

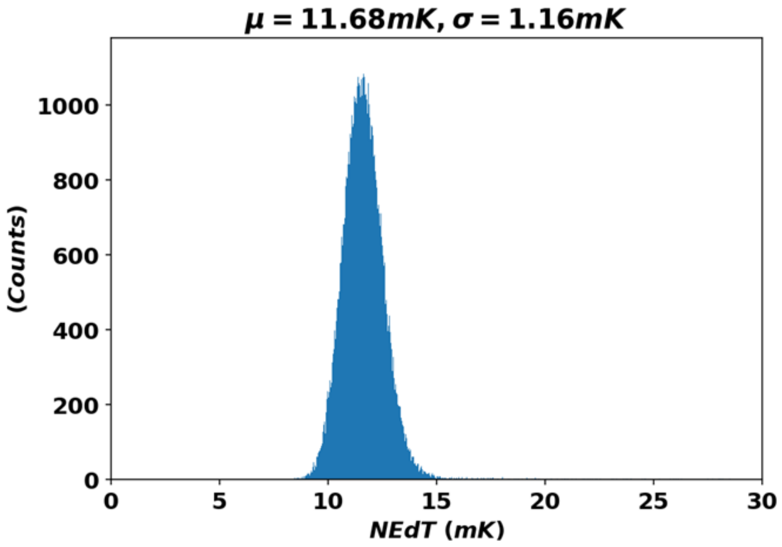
Camera under test

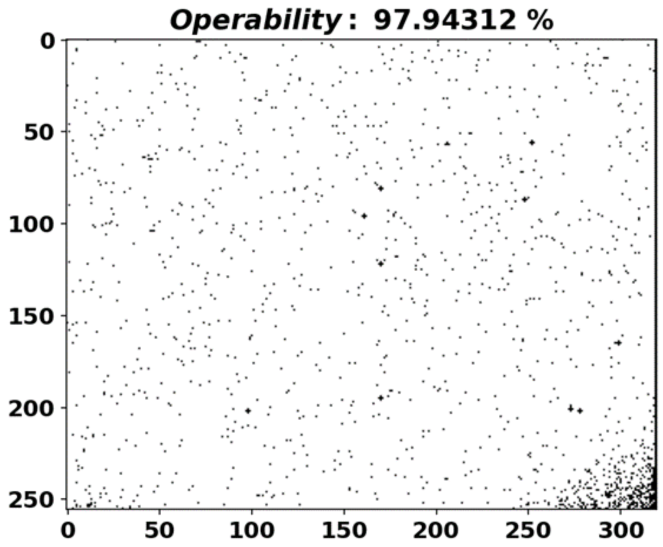
Imaging Test using Stirling Cooler

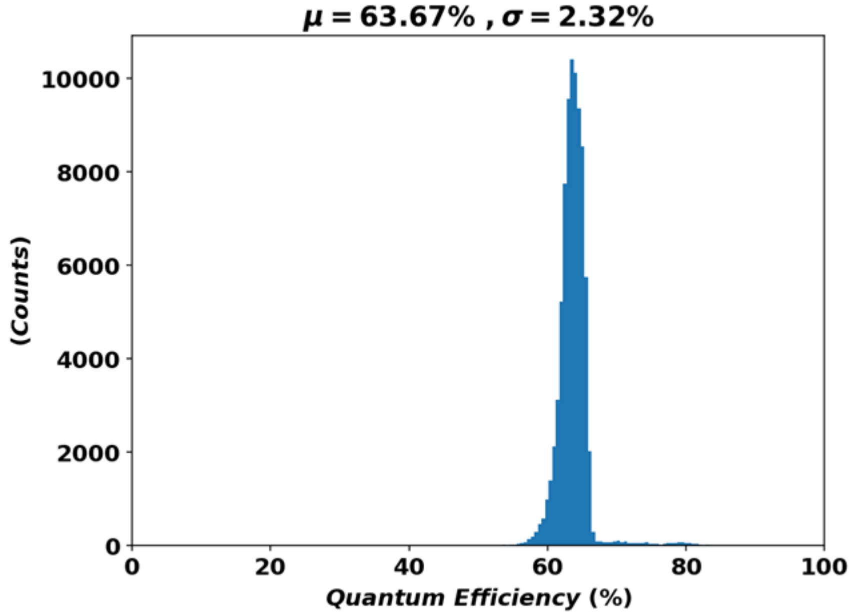












Summary and Future Works

- HgCdTe is the preferred infrared material for use in high radiation environment applications. EPIR has grown the HgCdTe wafers with desired characteristics using MBE
- Lateral collection device architectures were used to reduce dark current in implantation-formed p-n junctions. Photomasks were designed and FPAs were fabricated
- ROIC, LN2 Dewar and lenses tested at Fermilab: maintained functionality after 10^{12} n/cm^2 exposure, corresponding to ~ 1/3 year, 10^5 n/cm^2 continuous operation
- HgCdTe FPAs maintained functionality after 1.5×10^{13} n·cm^{-2} neutron exposure and 2×10^9 n ·cm^{-2} ·s^{-1} instant irradiation flux with only minor performance degradation. Equivalent to > 2 year continuous peak operation
- Most of the sub-optimal FPA pixels after irradiation can be recovered and restored to the original condition after temperature cycle (77 K to 300 K)
- Fabrication of IR cameras with high radiation resistance capabilities
- Will employ direct bonding to reduce cost and improve FPA operation stability
- We will continue to work with national labs for further testing of existing components and for testing new FPAs and cameras

LN2 cooled Camera head

Stirling cooler camera and MWIR image

THANK YOU